Conjoint analysis and virtual reality : exploring the possibilities

CONJOINT ANALYSIS AND VIRTUAL REALITY
EXPLORING THE POSSIBILITIES

Jan Dijkstra, Harry J.P. Timmermans, Walther A.H. Roelen

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Contents

1. Introduction

Conjoint analysis or experimental choice analysis represents a widely applied methodology for measuring and analyzing consumer preferences. Conjoint analysis is a generic term coined by Green and Srinivasan (1978) to refer to a number of paradigms in psychology, economics and marketing that are concerned with the quantitative description of consumer preferences or value tradeoffs (Timmermans, 1984; Louviere, 1988). Conjoint analysis, sometimes also referred to as stated preference modeling, involves the use of designed hypothetical choice profiles to measure individuals' preferences for choices of those new profiles (Oppewal, 1995). That is, multiple hypothetical alternatives (profiles) are generated according to the principles underlying the design of statistical experiments. These profiles are presented to subjects, who are requested to express their degree of preference for these profiles. Most applications of conjoint analysis involved a verbal description of profiles, although some studies have used a pictorial presentation. While such verbal descriptions may be acceptable in many choice contexts, our interest was triggered by the possibilities of virtual reality systems, which offer the potential of moving the response format beyond these traditional response modes. Virtual reality systems may be an interesting vehicle to develop interactive experiments, in which respondents more actively communicate with the designed profiles. Such systems may be important for designers wishing to assess the performance of their designs in terms of user preferences and behavior. Virtual reality systems, however, may also be used to measure consumer perception and more complex decisions tasks.

This report includes the first results of a stream of related research projects, which aim to explore the possibilities of developing a conjoint analysis and virtual reality system. This system has been given the acronym *ICARUS*, which stand for A System for Interactive Conjoint-Based Analysis in Virtual Reality of User Satisfaction and (Complex) Decision Making. The research activities are part of the VR-DIS[1] (Virtual Reality – Design Information System / Distributed Interactive Simulations) - research platform. We therefore start this report by discussing this research context. This is followed by a brief introduction of the basic concepts of conjoint analysis and virtual environments, leading to a description of the *ICARUS* system. Next, we discuss briefly some initial applications of the system to a variety of design problems. Finally, prospects of our research activities will be outlined.

2. Goals and Objectives of Research Project

2.1 The VR-DIS Context

This research project is part of the VR-DIS research platform, which was launched to develop a design information system in virtual reality. The platform is organized around three themes, one of which is concerned with the development of interactive user experiments. The concept underlying VR-DIS is described in Achten *et al* (1998). The particular focus of this research program concerns the integration of information from different disciplines within a dynamic design process, based on the new possibilities offered by virtual reality visualize design information.

Virtual reality as a user interface will probably replace many of the existing technologies because the man-machine interaction is closer to one's intuition. VR uses specific input and output devices that can stimulate all senses and capture various behaviors of users (Coomans and Timmermans, 1997). The challenge is to provide a new work environment that better support the design process. Such an environment would allow designer to work directly in 3D when designing spaces, would support collaborative design efforts, and could be used to interactively measure user

1) VR-DIS is part of the Design and Decision Support System in Architecture and Urban Planning (DDSS) research program of the Eindhoven University of Technology.

reactions to design alternatives in an attempt to measure design performance. All three lines of research are pursuit in the context of the VR-DIS research platform. The present research efforts are designed to investigate and develop a VR-DIS system that measures users' reactions, in terms of satisfaction, perception, and choice behavior to designs or design alternatives, both in architecture and urban planning.

2.2 Research Agenda

As mentioned in the introduction, most studies applying conjoint analysis have used a verbal format to describe choice alternatives. When visual information is important either to better understand the meaning of the attribute levels used to define the choice alternatives, or as a choice dimension in its own right, the verbal presentation format might imply a potential lack of realism. If this is the case, the reliability and validity of the measurement might be in doubt. Under such circumstances one would expect a graphical presentation format to lead to an improved reliability and validity. Therefore, some authors have used pictorial or multimedia information to describe the choice alternatives of interest (e.g., Klabbers and Timmermans, 1999).

In the context of the present study, we wish to take this reasoning one step further. If a graphic means of representation is better in particular circumstances, then one might argue that the actual experience of design alternatives in virtual reality might even be a better format. However, before when can start seeking answers to this research questions, a virtual reality system for conjoint analysis is required. Therefore, we set out to explore the possibilities for a technical perspective to develop such as system. This system should allow subjects or users to "experience" design alternatives, described in terms of multi-attribute profiles to bring them in a 'state of mind' that better resembles their actual decision-making in the real world.

Once a virtual reality system is built, in principle at least it is straightforward to extend the possibilities of the system and develop it into a full interactive measurement system that supports the design process beyond measurement of preferences/satisfaction. Due to their means of administration, traditional conjoint analysis was restricted to the preference/satisfaction and conjoint response formats. However, when the responses are observed in a virtual reality, it seems natural to expand the response format to *perception* and to various forms of *interactive, complex decision-making*. The focus on design has an immediate relevancy to design decisions that relate to perception (e.g., color schemes). The principles underlying conventional conjoint analysis can also be applied to this response format, except that a different measurement scale would be required. However, the possibilities of a virtual reality system go beyond this. Designers may be interested to learn which design feature catch the attention of the user. From a measurement point of view, it is often difficult to measure this directly as user often find it difficult to rationalize their decisions or make explicit their reasoning. Unobtrusive measurement would therefore be better, and it is especially in this regard that virtual reality systems have a lot to offer as user-tracking devices can be incorporated. Users may be asked to navigate through the virtual environment and their perceptions can be recorded. Users can also be asked to complete a given task, and the recording of their complex decision-making can then be used to assess the performance of the design alternatives in terms of such complex tasks. For example, it would be possible to assess the impact of different layouts on navigation and wayfinding. Likewise, layout, signage and functional properties of the design could be investigated in terms of user choice behavior. For example, the pedestrian behavior in buildings such as enclosed malls and in public spaces could be evaluated or simulated to better assess whether a design meets its goals in terms of comprehensibility, and navigation. It should be noted from the very beginning that such measurement does not necessarily have to be based on conjoint analysis. However, because the principles of conjoint analysis guarantee control over the covariance structure of the design attributes, the methodology does have particular advantages over non-experimentally based options. To better appreciate these advantages, we will now discuss the basic concepts of conjoint analysis in a little more detail.

3. Basic Concepts of Conjoint Analysis

Conjoint analysis is a family of related techniques for measuring user preferences or choice behavior. It has been developed to understand why consumers prefer or choose certain (new) products or services. It provides information about the relative importance of the attributes making up the choice alternatives and about the utility of the various attribute levels.

3.1 Traditional Conjoint Analysis

Conjoint analysis involves the measurement of consumer preferences or choices. It involves the study of the joint effects of multiple 'product' attributes on 'product' choice. A product in this context can be almost anything: a physical product, a building, a complex environment, a design, but also a service or a policy. It can already exist, or be beyond the domain of experience. We shall therefore talk about a choice alternative in the remainder of this report. Choice alternatives are viewed as bundle of attributes or attribute profiles. Each profile is a combination of attribute levels for the selected attributes.

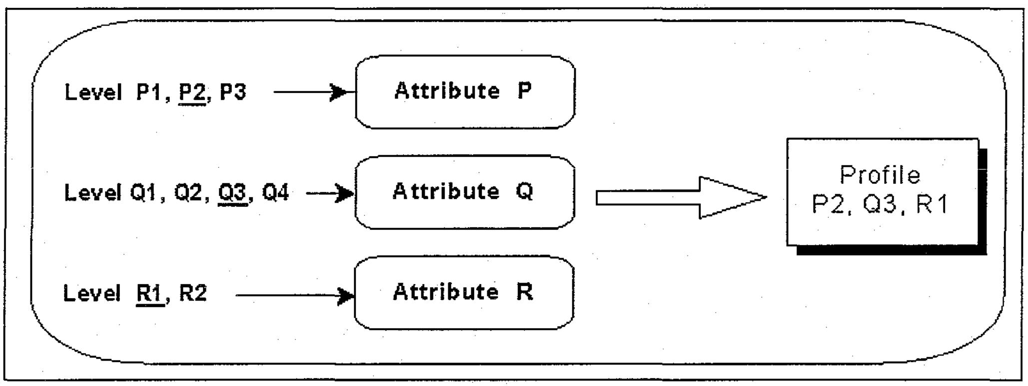


Figure 1. **Relationship among a profile, attributes and attribute levels.**

Conjoint analysis serves two major objectives:

1. to determine the contributions of predictor variables (attribute levels) and their respective values (utilities or part-worths) to user preference/satisfaction, and

2. to estimate a valid model of consumer (user) judgements useful in predicting user acceptance of any combination of attributes (Hair *et al*, 1995).

In order to achieve these objectives, coefficients called utilities (or part-worth) are estimated for the various attribute levels making upon the alternatives of interest by decomposing measured overall preferences for attribute profiles into these part-worth utilities according to some a priori defined combination rule, which specifies how subjects are assumed to integrate those separate part-worth utilities to arrive at an overall preference or choice. The utility or satisfaction of a profile is then calculated by combining these part-worth utilities of the attribute levels that define the profile according to some assumed combination rule. In most cases, an additive combination rule is assumed. Thus, if we let U_i denote the overall utility of choice alternative i, andx_{ik} denote the part-worth utility of attribute level k of alternative i, then

$$U_i = \sum_{k=1}^{K} x_{ik}$$

3.2 Experimental Designs

The estimation of the part-worth utilities involves varying the attribute levels according to some experimental design that satisfies the necessary and sufficient conditions to estimate the combination rule or utility function of interest. Consequently, profile construction in conjoint analysis involves determining which attributes to present to subjects, and how to present them. In a conjoint experiment, first the key attributes of choice alternatives are identified. If the focus is on measuring consumer utility, then the most important attributes should be elicited. If, on the other hand, the focus is on measuring consumer reaction to design attributes, the design dictates the selection of attributes, which might not be important in terms of influencing preferences or utilities.

Next, the specific levels of each attribute are chosen. The chosen attribute levels should be realistic and relevant to the problem. In addition, the ultimate definition of attributes and their levels will be influenced by the possibilities of constructing a suitable experimental design that satisfies the necessary and sufficient conditions, required to estimate the assumed preference or choice model. Consequently, the design of such experiments involves considerable expert knowledge, especially in the case of complex designs..

Having selected the attributes and their levels, some experimental design is used to systematically vary the attribute levels of interest. Conjoint experiments thus require individuals to express their preference for various experimentally designed hypothetical choice alternatives. Two or more fixed levels are defined for each attribute and these are combined to create different profiles. For example, hypothetical shopping centers can be described in terms of the number of stores, distance from home, and parking convenience, as shown in Figure 2. (Timmermans *et al.* 1984)

Number of shops:	Small	[medium; large]
Travel time:	15 minutes	[30; 45]
Parking search time:	4 minutes	[12; 20]

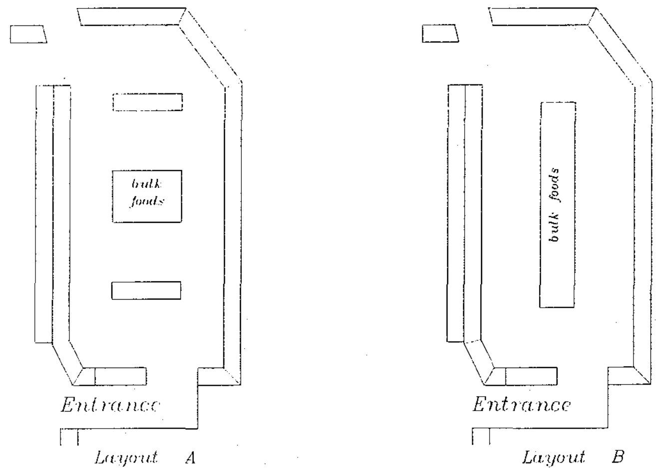
Figure 2. **Profile of a hypothetical shopping center, as used by Timmermans et al. (1984). The right-hand column displays other possible levels to define alternative profiles.**

Subjects are invited to express their preference for the experimentally varied profiles by rating or ranking these in terms of overall preferences. Alternatively, subjects may be asked to choose the profile they like best. For example, in the study by Timmermans *et al* (1984), subjects had to rank nine profiles. Preference functions are estimated from such rating, ranking or choice data. Obviously, the number of possible combinations increases immensely with an increasing number of attributes and/or attribute levels. For example, six attributes each with three levels produce $3^6 =$ 729 possible combinations. Such combinations are known as a full factorial profile experimental design. In any realistic problem, the evaluation of all possible combinations represents a very demanding and unrealistic task. Therefore, it is common to rely on fractional factorial design techniques (Montgomery, 1991). In analysis-of-variance terms, this often means that only main effects can be estimated, assuming that the interactions between attributes are negligible. In the current example with six three-level attributes, the use of a fractional factorial design reduces the 729 possible profiles to only 18 profiles.

3.3 Design and Analysis of Conjoint Choice Experiments

The previous discussion, strictly speaking, relates to a preference model. A subject's preferences are decomposed into its part-worth utilities, which represent the contribution of the attribute levels that were used to construct the profiles to the subject's overall preference or utility. When the goal of the study is to measure preferences, utility or satisfaction, then the present design strategy would suffice. However, often the aim of the study is to predict choice probabilities of market shares. For example, how many respondents would be willing to buy a particular house, designed in a particular way. Answers to such questions require the construction and estimation of a choice model. To estimate a choice model, the design of the experiment involves placing the attribute profiles into choice sets. Subjects are then asked to choose one alternative from each choice set or, alternatively, to allocate some fixed budget among the choice alternatives (Oppewal and Timmermans, 1991).

We will illustrate some of the above issues by presenting a simple example.



Let us assume that a retailer has to decide how to design the first aisle after the entrance in a supermarket. In making his decision, the retailer has to consider a number of factors. Let us assume that the following attributes and their levels are important:

- *Merchandise indication (MI)*
  should there be an indication of the merchandise category (for instance 'fresh meat', 'cheese chop'), which is highly visible from a distance?
  No = no indication, Yes = indication

- *Bargain offers near at the entrance (BOE)*
  should bargains be exposed near the entrance?
  No = not desirable, Yes = desirable

- *Layout (LO)*
  what would be the best layout prefer?
  A = layout A, B = layout B

Summarized, in this simple, illustrative example, we have the following attributes with their levels:

Attributes	*Levels*
MI	Yes, No
BOE	Yes, No
LO	A, B

These attribute levels can be combined, yielding a total of 8 (=2^3) possible profiles.

Profile 1	....	Profile 8
• MI : No		• MI : Yes
• BOE: No		• BOE:Yes
• LO : A		• LO : B

Consumer satisfaction with each of these profiles can be measured in a variety of different ways, using different response formats. In case of ratings data, subjects are requested to rate these profiles on some psychological scale. Such rating data provide information about the order and degree of preference. For example, a question could be: how would you rate the following profile on the following scale, ranging from very poor to very good?

Profile 1
MI : No
BOE : No
LO : A

X
1 2 3 4 5 6 7
very poor — average — very good

In case of choice data, profiles are placed into choice sets and subjects are asked to choose among two or more profiles. For example, which profile do you prefer?

Profile 1	Profile 8
• MI : No	• MI : Yes
• BOE : No	• BOE : Yes
• LO : A	• LO : B

Finally, in case of budget allocation, budget-points will be allocated among a set of profiles. For example, a budget allocation with profiles 2 and 7 as hypothetical alternatives, could be:

Allocate 20 budget-points	Basic Profile .... points	Profile 2 .... points	Profile 7 .... points

'Design descriptions'

The principles to construct the choice alternatives rely on the choice of an experimental design that optimizes the identification of the utility function. The most commonly used approach is the *full profile approach*, which involved the combination of all attributes. If we design involves all possible combinations of attribute levels, the design is a *full factorial design*, if only a fraction is taken, the design is a *fractional factorial design*. A Full Factorial (FF) design enables one to independently estimate all main effects and all interaction effects of all attributes. In contrast, a Fractional Factorial design assumes that certain interaction effects among the attributes are negligible and hence can be ignored. By ignoring such interactions, only a fraction of all possible combinations is required to estimate the preference function, that will typically consist of all main effects (the effects of all individual attribute levels to overall utility), plus perhaps some selected interaction effects between two attributes. The following simple example will illustrate the two types of designs. Suppose we have 3 attributes with 2 levels each, represented by 0 and 1 respectively. A 'Full Factorial' (FF) design exists of all possible combinations.

Combination/Profile	Levels
1	0 0 0
2	0 1 0
3	0 0 1
4	0 1 1

5	1 0 0
6	1 1 0
7	1 0 1
8	1 1 1

In contrast, a 'Fractional Factorial' design exits of a fraction of the FF design. For example:

Fraction 1		Fraction 2	
Profile	levels	Profile	levels
1	0 0 0	2	0 1 0
4	0 1 1	3	0 0 1
6	1 1 0	5	1 0 0
7	1 0 1	8	1 1 1

In most applications, and illustrated by the above example, an orthogonal fraction is used. It implies that the correlation between all pairs of attributes is zero, implying that the preference function can be estimates in an unbiased manner.

4. Virtual Environment

Having discussed some of the basic principles of conjoint analysis and before discussing our system, let us now spend a few words on virtual reality. Starting point for us is that virtual reality is a natural extension from 3D modeling and simulation. The additional realism conveyed through real-time interaction, stereoscopic visualization and the sensory 'immersion' in the illusory world provides designers with new powers of expression and the means to compose new spatial experiences on the other. What distinguishes VR is the crucial role played by the user, who is actively involved and not a passive observer. The user becomes an essential participant in the virtual environment with unlimited freedom to explore, control and change it. The only limits are those set by the designers of the virtual environment (Engeli and Kurmann, 1996). In contrast to conventional CAD systems, VR supports for activities which characterize the early conceptual phase of design, called 'prototyping of designs in virtual reality' (Coomans and Oxman, 1996). VR techniques can be used to create an interface that allows intuitive modeling. The design can be visualized, design changes can be made, and new concepts, without the traditional expense of prototyping, can be tested.

These characteristics have an immediate impact on the design process itself. However, virtual reality can also be used to measure user satisfaction and decision-making. If the designer or expert can move through a design, user can do so too. It allows the assessment of the design in terms of user satisfaction, choice and other aspects of decision-making. Are the design intentions consistent with user reactions? How do they evaluate particular aspects of the design. Is the layout comprehensible? What would happen in case of a fire alarm. Would evacuation be on time? Does the distribution of functions enhance particular kinds of behavior? Advances in VR techniques now enable consumers to be immersed in new environments and experience new choice options. It is especially this aspect that motivated the development of the *ICARUS* system, which will be described in the next section.

5. *ICARUS*

Most studies of conjoint analysis have involved verbal descriptions of attribute profiles, although some studies have used a pictorial presentation. Vriens (1995) investigated whether conjoint results depend on the presentation format, when both pictorial and verbal representations are feasible. He distinguished conceptual differences between the two formats. These conceptual differences concern:

- the possibility to include design, styling or aesthetic aspects as an integral part of hypothetical products;
- the type of information processing induced by the respective format. Pictures tend to be processed simultaneously in an imagery system, whereas verbal representations are processed sequentially in an independent verbal system;
- the degree of task realism. Pictorial representations contribute to the degree of task realism of the evaluation task.

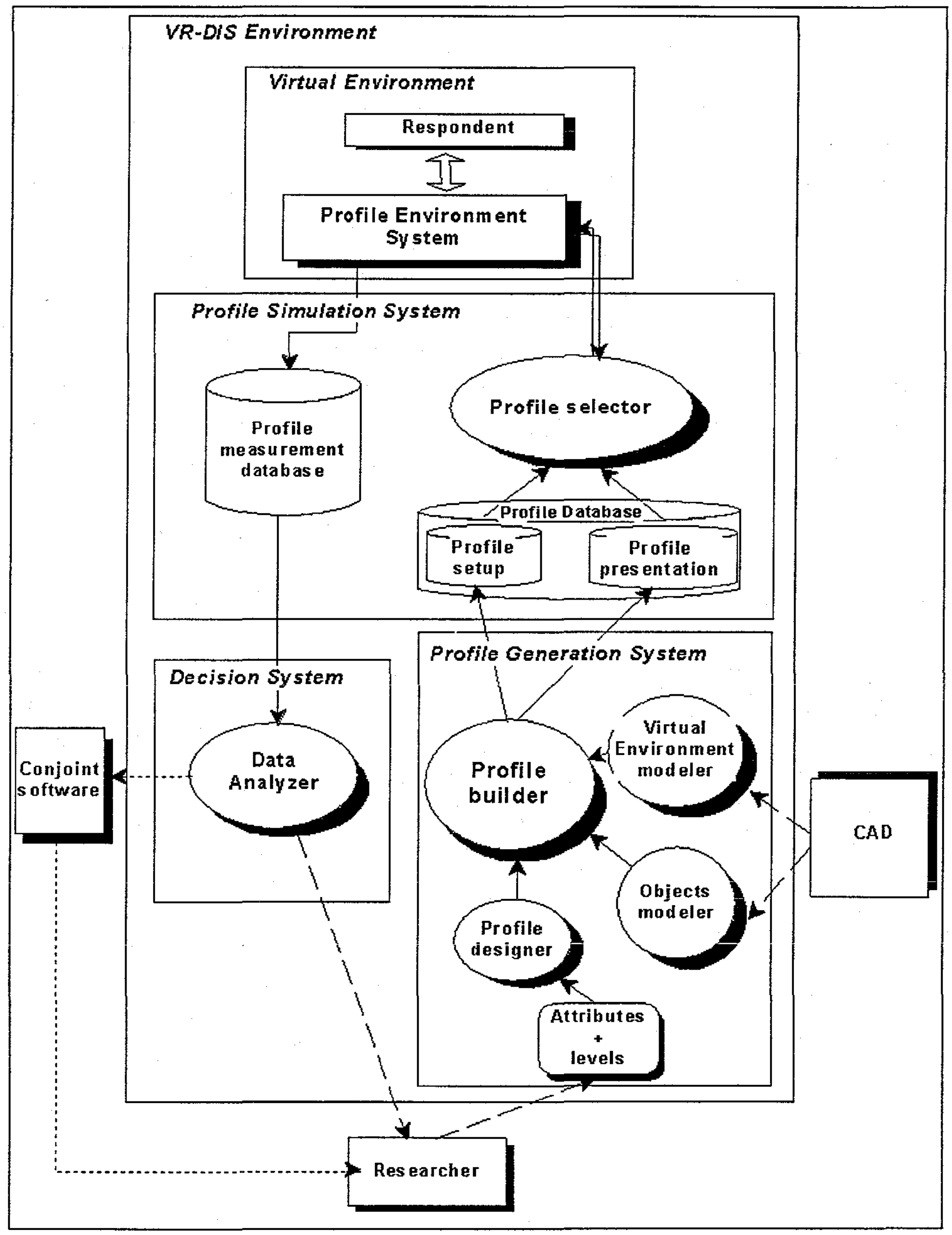


Figure 3. **Components of *ICARUS*.**

Klabbers *et al* (1996) propose a multimedia engine for stated choice and preference experiments, which enables researchers to use varying presentation formats (textual, pictorial, auditory presentations and combinations), thereby measuring the influence of the presentation format. Pictorial presentation of attributes can lead to more reliable and valid measurements of utilities. To get a better insight into user subject behavior, it is desirable to improve the realism of the hypothetical situation to ensure that the subject is making a 'real' decision. Virtual reality techniques may be of interest in this context.

The *ICARUS* system is being developed against this background. A first description was given in Dijkstra, Roelen and Timmermans (1996). The quintessence of the system is that profile descriptions are depicted in a three-dimensional virtual environment and that subjects are allowed to interact with these profiles. A profile consists of a virtual environment model and dynamic virtual objects representing the attributes with respective levels. Each attribute level is a different state of the concerned virtual object. Both the virtual environment and objects model can be designed by 3-D graphical and virtual reality software. Conjoint measurement is used to vary these profiles in a systematical way that allows the valid estimation of preference functions.

The components of the *ICARUS* system are given by Figure 3 (previous page). The *Virtual Environment* relates to the person (subject) that indicates his/her preference by choosing among selected profile alternatives, or demonstrating other types of behavior. The *profile Simulation System* consists of profiles-sets, including the profile set-up and the profile presentation (virtual design). It also regulates the random selection of choice alternatives in choice set of profiles, and records user responses according to the particular response format in the virtual environment. The *Profile Generation System* allocates the attribute profiles and attribute levels, necessary for the experimental design. It also generates this design, the profile set-up, the representation of the profiles and the profile-environment and profile-objects. The *Decision System* is responsible for the analysis of the measurements.

The architecture of the system was build with agent-technology in mind. Huhns *et al* (1998) define agents as active, persistent (software) components that perceive, reason, act, and communicate. Thus, *ICARUS* can be considered as a multi-agent system in the sense that it is composed of several agents capable of mutual and environmental interaction.

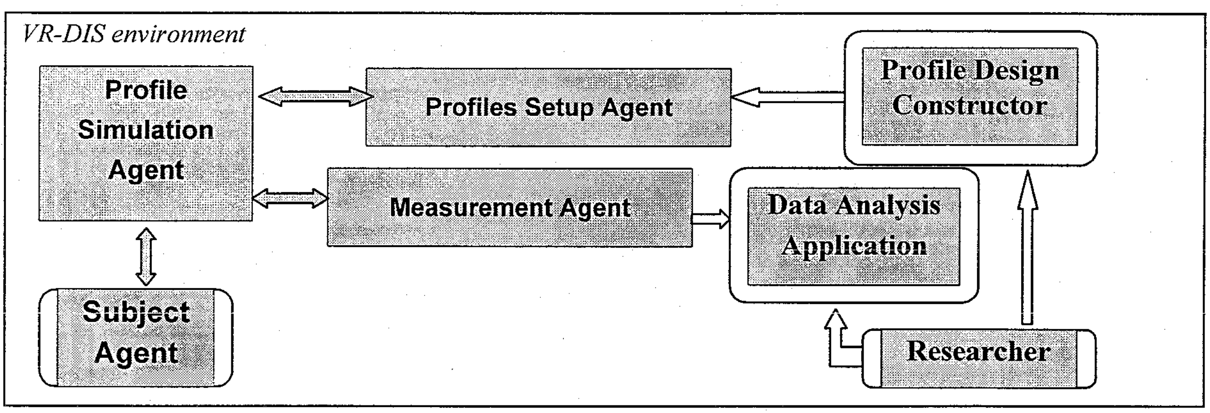


Figure 4. **The multi-agent system.**

This means that *ICARUS* consists of system components and a number of agents with communication channels between them, designed as a collection of interacting (autonomous) agents, each having their own functionality and goals and situated within a common environment, the VR-DIS environment. The following agents can be identified (Figure 4):

- the *Subject Agent*: the person who navigates through the profile virtual environment. Perceptions can be measured and actions can be taken. The goal is to complete a task in the profile virtual environment.

- the *Profile Simulation Agent*: simulation of a virtual environment of a selected profile alternative. When a subject activates the static profile environment, virtual objects describing the profile attribute levels will be loaded. Communication with the 'measurement agent' takes place to record user behavior.

- the *Profiles Setup Agent*: selection of a profile alternative, or profile alternatives in the case of choice sets (profile selector). Besides the profile selector, the profile database is part of this agent. The profile database consists of the profiles-setup, that is the product profile descriptions (attributes and their levels) and accompanying product profile presentations (virtual design objects).

- the *Measurement Agent*: measurement of response data and recording of user behavior.

- the *Profile Design Constructor Agent*: generates the profile-design, both the profile attributes and attribute levels (profile designer), and the profile virtual objects (objects modeler). The static profile environment(s) will be generated, too. The profile-setup and their representation are supplies the input for the profile databases.

Agent		**Percepts**	**Actions**	**Goals**
Subject		Perceptions	Decisions	Fulfilling a task
Profile Simulation		Perceptions, answers	Questions, registrations	Virtual interaction, preference measurements
Profiles Setup		Messages	Selections	Presentation of a profile alternative
Measurement		Messages	Measurements, registrations	Conjoint measurement, registration user behavior

Figure 5. **Agent description.**

This architecture is motivated by the possibility to create 3D representations of environments, varied according to the principles of experimental designs, allowing controlled observations of user reactions to design alternatives. By recording these observations in a particular way, various statistical and non-statistical methodologies can be applied to evaluate design alternatives or predict user reactions.

6. Illustrations

To explore the potential of the system, we have developed some simple prototypes. The various prototypes demonstrate the potential of the system to analyze preferences, perception and complex decision making respectively. In the following sub-sections, these prototype applications will be described in more detail.

6.1 Measuring Preferences: the Design of Signage in the Context of Wayfinding

The first example concerns the measurement of user preferences for signage. Graphic symbols used to improve wayfinding in buildings can be designed in many different ways. The purpose of this prototype application was aimed at developing a virtual reality system that supports the measurement of user preferences for various profiles, using conjoint analysis. This application will be discussed in the following sub-section.

6.1.1 Wayfinding concepts

Most settings are laid out in a plan people can relate to and which allows them to determine their location within the setting, determine their destination within that setting, and form a plan of action that will take them from their present location to their desired destination. The representation people have of their surrounding environment is a psychological concept that underlies the notion of spatial orientation. This is called a cognitive map, which is an overall mental image of the spaces and the layout of a setting.

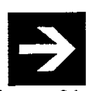
One way to get a better understanding of the various aspects of wayfinding is to think of it in terms of the 'human-machine system'. A human is considered as a system in which receptor (sense-) processes, mental (information-processing, deciding) processes and effector (acting-) processes play a significant part during his different activities. In any case, the decision to find one's way can only be made by receiving adequate information through perception, cognition and exploration. In this context, two aspects are of interest, namely the aspect of 'content of information' (decision making) and the aspect of 'form of information' (perception and cognition).

These aspects of information can also be found in Passini (1984). Wayfinding was the term introduced to describe the process of reaching a destination. Wayfinding concerns the spatial organization of the setting, the circulation system and architectural as well as graphic communication. It can be described as all perceptual, cognitive, and decision-making processes necessary to find one's way, that is as a mental and physical act of reaching destinations (Arthur and Passini, 1992). The process of reaching a destination is best defined as spatial problem solving, comprising of three specific but interrelated processes:

- *Decision-making*, the development of a plan of action.
- *Decision execution*, which transforms the plan of action into appropriate behavior at the right place in space.
- *Information processing* understood in its generic sense as comprising environmental perception and cognition, which, in turn, are responsible for the information basis of the two previous decision-related processes.

Besides the spatial problem solving aspect, there is also the architectural and graphic communication aspect of wayfinding. The spatial organization of a setting and the circulation system determine the nature of wayfinding problems. Environmental communication provides the information necessary to solve wayfinding problems. In terms of wayfinding communication, designers have to respond to three major questions: what information should be presented, where and in what form (Passini, 1996). Therefore, the design part provides information, identified by three aspects:


content of information


location of information

form of information

People tend to feel disoriented when they cannot situate themselves within a spatial representation and when, at the same time, they do not have or cannot develop a plan to reach their destination. The decision to find one's way can only be made by receiving adequate information through perception, cognition and exploration. Developing signs can solve wayfinding difficulties. In virtual wayfinding, the visual environment will be simulated and people are located at a virtual setting in this environment. They find their way from the present location to a desired destination by making a walk-through in the virtual environment. During virtual wayfinding, people will select that information which is relevant to their task. Information, based on the three aspects of information mentioned before, will be presented as different virtual design objects in the virtual environment.

6.1.2 The wayfinding experimental design

Graphic communication may at least partially compensate for possible flaws in architectural design. In Dijkstra *et al* (1996) and Dijkstra *et al* (1997b), an illustration of wayfinding was given focusing on this aspect, which often is of crucial importance in facility management. Thus, in the experimental design, the graphic communication was considered. Graphic communication includes signs, maps, directories and good sign posting, etc. In graphic communication, functional information type will be emphasized. That is, functional information type is considered in relation to those things that people need in information settings:

- information about the settings, the way it is organized (information to make decisions),
- information directing them to their location (information to execute decisions), and
- information identifying the destination on their arrival (information to conclude the decision-making/execution process).

These types of information comprise attributes in the *ICARUS* system. Each of these attributes has two levels. Together, the number of attributes and their associated levels comprise the design specifications. The experiment also measured the travel-time from the entrance to destination.

To appreciate the potential contribution of the system, we let subjects experience two possible guidance alternatives and ask them to express the one they prefer. Obviously, this is the simplest application that stays closest to the traditional use of conjoint choice and preference models.

Attribute	Level	Description
◊ Orientation	⇒ Floor plan ⇒ Directory	Ability to perceive an over-view of a given environment
◊ Directional signage	⇒ Text besides arrow sign ⇒ Text inside arrow form	Guides people along a designated route to a destination
◊ Identification	⇒ Name ⇒ Sign with name	Information provided at the destination

	Identification: *Name*	Identification: *Sign with name*
For instance:		

Figure 6. **Experimental design specifications.**

6.2 Unobtrusive Measurement of Perceptions

The second illustration was intended to show that the system could also be used to measure preference unobtrusively. This application can support design decisions especially when the focus is on the identification of cues that capture user attention and /or influences user behavior. It involves eye-tracking techniques. The context and a simple illustration will be discussed in the next sub-section.

6.2.1 Eye tracking as a user behavior registration tool

As visually oriented creatures, humans use their eyes intensively for a large variety of purposes, such as for reading, watching, gathering information to plan their actions, perceiving and learning new things, and exploring and navigating in environments. Generally, we do not realize how great an effort our eyes put into our perception process, and what immense amounts of information they process. We can concentrate our cognitive processes by operating on the concepts that surround us, leaving the intake and basic processing of optical information to our eyes and visual system. We observe the surroundings, which is also the most important role of our eyes. In this way, the eyes are used as INPUT -organs. But eyes can also operate as OUTPUT -organs; the output they are capable of producing is, on the face of it, direction. The eyes are pointed in one direction, thus indicating what is being focused upon (Glenstrup and Engell-Nielsen, 1995).

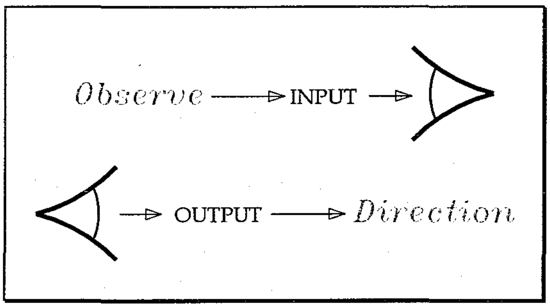


Figure 7. **Eyes as input- and output organs.**

By eye tracking techniques, it is possible to monitor the orientation of eyes, and thus the direction of gaze. The ability to track the direction of gaze enhances the communication between the subject and the computer. By tracking the direction of the gaze of the user, the amount of potential information transfer can be increased by using the information about what the user is looking at, and even designing objects specially intended for the user to look at. By monitoring the user, the computer can react to all kinds of gestures. In this way, what the user is really interested in becomes more transparent. As a positive consequence of eye-gaze interaction, handicapped people for example are allowed to concentrate on interacting with the data presented by the computer. That is a new way of regarding the computer not only as a tool that must be operated explicitly by commands by one that can also be operated visually.

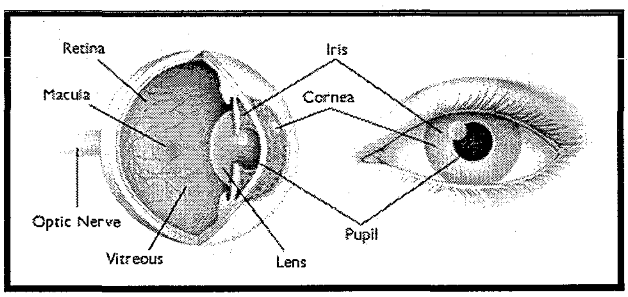


Figure 8. **Eye representation.**

Eye tracking works, but only under controlled conditions. There are two methods of eye tracking, which are most commonly used: limbus tracking and video tracking. Limbus tracking works by illuminating the eye of the user with an invisible near-infrared LED. A photodetector is used to pick up the intensity of reflected light from the white, or sclera, portion of the eye. The iris and pupil represent the dark regions of the eye. The intensity of reflected light would vary with the eye position because of the varying proportion of the light and dark regions of the eye exposed to the detector.

Video tracking on the other hand works on the principle of Pupil Center/Corneal Reflection (PCR). The eye is illuminated with a near-infrared LED. A video camera collects images of the eye. From these images, a computer calculates the center of the pupil and the specular highlight of the LED, which is referred to as the corneal reflection. Because the lens of the eye protrudes out in front of the sphere of the eyeball, the pupil and reflection move relative to each other as the eye shifts gaze. The computer uses the vector between the pupil center and corneal reflection to calculate the direction of the gaze. With either method, a calibration process is used to relate eyeball motion into point of gaze that relates to the real world.

On video tracking systems, in some cases the optics are fixed to the room and the system can directly measure eye line of gaze with respect to the room. This system (called *remote system*) is an eye tracking system, which is not attached to the user being tracked. It may be attached to the floor by a tripod, or perhaps sitting on a table near a display which the user is looking at. In other cases the optics are fastened to the user's head or to a helmet or headband worn by the user and eye line of gaze is measured with respect to the head (*head mounted* system). A head-mounted system can measure no matter how the user turns his head or what he holds. A great deal of user freedom is possible although the user does have to wear some device, and the measured quantity is eye line of gaze with respect to the head. If you need to know the point of gaze on a stationary scene or object, either the head must be rigidly fixed or the position and orientation of the head must also be measured. The necessary head reference can be provided by a head mounted scene camera and/or by one of several head position detection systems.

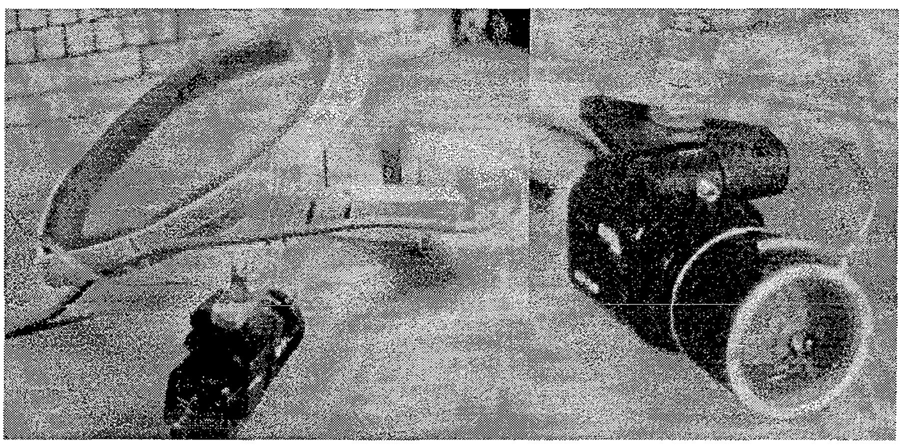


Figure 9. **Heads-Up unit, the miniature camera.**

The application of eye tracking techniques to the field of architecture has hitherto hardly been explored. Studies of eye movement have traditionally dealt with normal reading, reading disabilities, visual tracking and scanning. Studies, which emphasize the influences of formal characteristics in visual patterns, have been undertaken. Noton and Stark's (1971) studies pertain to the physiological and cognitive foundations of eye movement with a particular focus on scanpath patterns. The scanpath has been defined as a repetitive sequence of saccades and fixations, idiosyncratic to the viewer and to the picture.

The project 'Oculomotor Research in Architecture' by Weber (1996) represented an attempt to record how the visual experience of architecture is influenced by various formal-geometric characteristics. The study was undertaken with the use of computer-controlled video equipment measuring scan-path of the human eye during the perception of three-dimensional architectural models according to the remote video tracking system. It shows how people look at buildings and architectural spaces; what elements of architectural form trigger the attention of the eye more strongly than others and how spaces are perceived when architectural elements are altered of replaced. One of the most important apparent findings of this initial research in relation to architectural issues appears to be that the perception of architectural forms and spaces is not based on the scanning of individual stimuli, such as contours, but on forms as a whole.

6.2.2 Registration of user behavior in virtual environments

To what extent users are interested in specific design concepts can be based on measurement of visual attention by eye movements. The perception of a scene in a virtual environment involves a pattern of fixations, where the eye is held fairly still, and saccades, where the eye moves to a new part of the scene. Eye movements can be measured by eye tracking techniques.

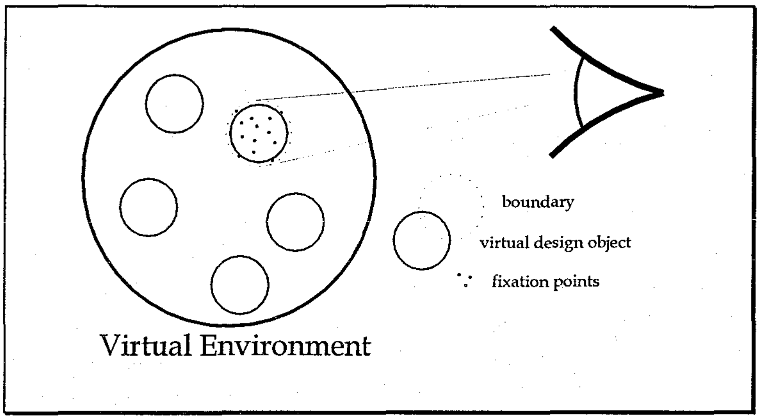


Figure 10. **Visual attention field.**

Eye movement measurement allows one to determine which areas of the scene in the virtual environment act as visual attention fields, on which the eye focuses longer fixation duration. Let $FT_{o,1}$ denote the measured fixation time on the visual attention field of the virtual design object. Fixation time is the elapsed time of fixing one's eye on the visual attention field, which is determined by the boundary (region) of the virtual design object. Consider a profile of n design objects of interest. The total fixation time then is the summation of the fixation time of each virtual design object:

$FT_i = FT_{o,1} + \ldots\ldots + FT_{o,n}$; $FT_i =$ total fixation of profile

6.2.3 A simple illustration

A design was presented by a virtual environment model and dynamic virtual objects representing the different design aspects (called attributes) of interest with their respective levels. Each attribute level is a different state of the concerned virtual design object. We considered the functional design aspect of wayfinding with the emphasis on the use of graphics. In this illustration the attribute 'orientation' involves the ability to perceive an overview of a given environment, which has two proposed levels: *floor plan* and *directory*. Also other graphic components were considered, like 'directional signage' and 'identification'. All these graphic components were presented as different virtual design objects in the virtual environment. A given situation of the graphic component attributes represents a product profile. In this case of virtual wayfinding, indications like signs presented as different virtual design objects could be tested for their suitability. The perception of virtual design objects in the virtual environment gives the necessary feedback. With a head-mounted eye tracking system, this feedback will be given by measuring the duration of fixation on the visual attention fields of virtual design objects. As a perceptual task becomes more difficult, by definition the time to perceive objects increases. In a perceptual task that involves scanning virtual design objects, this change is correlated with a change in one or more eye movement parameters. The parameters of eye movement involved in the perception of virtual design objects are duration and the location of eye fixations. Fixation time on attributes can be assumed to reflect the effectiveness of the concerned attributes. Randomization in experimental design helps to reduce undesirable effects of a subject's expectations and strategies. We let subjects experience two profile alternatives and measure the fixation time on each attribute of each profile as well as the total fixation time of each profile. The total fixation time (*FT*) can be considered to be a measure of the computed level of interest or effectiveness. An experimental design can be used to vary the attributes of interest.

We are not interested in fixation at a certain point of gaze but in eye fixations at visual attention fields. Therefore, the head-mounted eye tracking system was simplified by head tracking. Subjects wear a headband with a head position-sensing device, which transmits positional information to the scene of the virtual environment. Head motion was measured, while navigating through the virtual building. The projected image of a 3D-cursor in virtual space should align visually with the real position of the 3D-input device that controls it (Hall, 1997). To refine the illustration, aspects considered were (i) testing design objects for their suitability by measuring fixation time involves the use of more virtual building alternatives, (ii) how accurately the eye position must be with respect to the head be measured, and how far the user can move his head, (iii) eye movements and therefore fixation time can be influenced by attention for the hand-eye coordination (Hall, 1997).

6.3 Measuring Interactive Complex Dynamic Decision Making

In addition to measuring preferences and perception, the system can also be used for measuring more complicated forms of behavior. For example, subjects may be asked to complete different complex tasks or "games" in a virtual environment. Examples of such tasks would be to select a route, to spend some time, or schedule activities in time and space, etc. The following application considers the problem of finding the exit of the building. Measuring whether users are successful in this regard, or measuring the time it takes to complete this task provides critical information to evaluate design alternatives in this dimension.

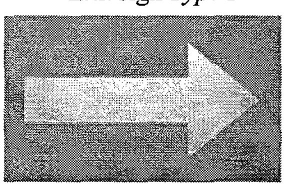
6.3.1 The experiment

This illustration focused on information directing people to the exit of the building. It was meant to better understand the suitability of exit-signs. Besides the aesthetic aspect that could be measured, the prototype was aimed at developing a mechanism to measure the effectiveness of exit-signs. The conjoint experiments involved three attributes. Each of these attributes had two levels. Together, the number of attributes and their associated levels comprise the experimental design specifications in the illustration.

Attribute	Level	Description
◊ Directional Exit-Sign Location	⇒ Fixed at wall, column ⇒ Fixed at ceiling	Guides people along exit-route to exit
◊ Directional Exit-Sign Type	⇒ Exit sign I ⇒ Exit sign II	Guides people along exit-route to exit
◊ Exit Identification	⇒ Exit Font I ⇒ Exit Font II	Information provided at exit

For instance:

Exit sign *Type I*



Exit sign *Type II*

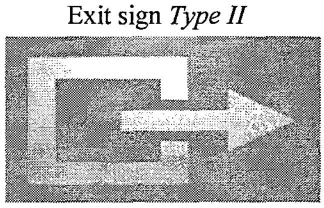


Figure 11. **Design specifications.**

The scenario underlying the experiment involved a walk through the building, going to a destined meeting-room. In a fire drill simulation, during a smoke production, the task of subjects was to their way from the meeting room to the exit within a certain time-period. The individual selects information from the available signs, as displayed in profile alternative 1. After this, subjects were placed back into the meeting-room. After a new fire drill simulation, they found their way-out again. In this case, subjects selected their information from signs, designed according to profile alternative 2. The elapse time and whether the task was completed within some time frame provide the information requires to estimate the effects of design decisions, varied in the experiments, on success rates or elapse time.

7. Prospects

We have demonstrated the potential of the *ICARUS* system as a tool to support design decisions. In particular, we have argued that the system can be used to measure and assess the impact of particular design decisions on user satisfaction, perception and complex decision-making. The system is based on conjoint analysis, which implies that the design variables or parameters should be defined into attributes and attribute levels and varied according the principles of the design of statistical experiments. While this experimental design approach is not really necessary (users may also be requested to perform the same tasks for particular design alternatives that do not adhere to some experimental design), the use of conjoint experiments is that the researcher has full control over the covariance structure of the design variables, allowing a more valid and reliable assessment of design performance.

When the response format concerns the measurement of satisfaction (preference), the application is consistent with traditional conjoint analysis, and consequently the conventional statistical techniques can be used to analyze such data. When the system is used to measure perception, as indicated by fixation time, the dependent variable shifts from satisfaction to time. Consequently, other statistical models than those traditionally used in conjoint analysis are required. For example, when fixation time is treated as duration data, a hazard model may be applied to assess the influence of design variables on perception. Similarly, the use of success rates is not conventional in conjoint analysis, and different statistical models are required. Success rates could be analyzed using a binomial logit model.

The use of VR systems allows the creation of interactive environments. *ICARUS* can be used to observe user reactions and decision making in environments not yet existing. Such a system allows the evaluation of an a priori building performance. Especially, it offers an opportunity for generalizing the findings beyond the actual environments that were incorporated in the virtual environments. When users are requested invited to express their preference for the experimentally varied profiles by rating or ranking these in terms of overall preferences, satisfaction measurement can be obtained. By measuring fixation time at visual attention fields of virtual design objects, it is applied for perceptual tasks.

Perhaps the most interesting but also the most challenging is to use the system to conduct interactive computer experiments and measure complex forms of user behavior. The main goal in this case would be to unravel behavioral decision making and explore how user arrive at their choices. The relevance of this format is emphasized by the fact that many real-world decision tasks are dynamic in nature, which often means that the decision context changes over time. Dynamic task situations, however, are rather difficult to model. There is an exponential growth of possible outcomes over time. The complexity of the situation is appreciated if it is realized that the environment in which the decisions are made may be changing, either as a function of the sequence of decisions, or independently of them, or both. Moreover, decisions need to be made in real-time. This factor adds an extra dimension to dynamic decision making, as the decision-maker has to consider the dimension of time explicitly. It is not enough to know what should be done but when it should be done. Thus, in dynamic tasks subjects typically face a changing system, they receive feedback about the state of the system and they need to make a sequence of decisions. Finally, decisions change over time. The main effect of the changing nature of dynamic tasks is that the time dimension has to be taken into account explicitly.

The results described in this report are all based on prototyping. A full appreciation of the potential of the system warrants the actual testing and application of the system to particular empirical problems, involving actual data collection. It is our intention to start this process in the near future.

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Some basics of eye tracking systems and pictures are derived from the 'ASL Eye Tracking Systems Handbook' of Applied Science Laboratories, Bedford, MA, USA.

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