Improvement of Perception and Cognition in Synthetic Spatial Environments

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Vorwort

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Fachgebiet für Flugmechanik und Regelungstechnik der Technischen Universität Darmstadt.

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Ich versichere an Eides statt, daß ich diese Arbeit mit Ausnahme der ausdrücklich erwähnten Hilfen selbständig durchgeführt habe.

La Fare les Oliviers, im November 2000

Besondere Danksagung

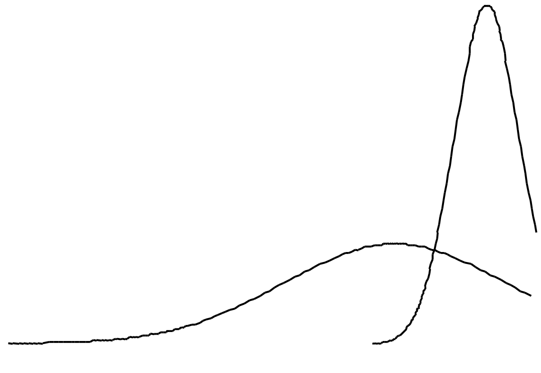
An dieser Stelle möchte ich den Freunden danken, die mich während der Promotion begleitet haben, und die die guten Erinnerungen an die Zeit in Darmstadt bestimmen werden.

Dazu gehören besonders:

Die Mitglieder des Cavok Teams, die mich sowohl persönlich als auch wissenschaftlich unterstützt haben.

Meine Familie, im Besonderen meine Eltern, die mir bis heute den von mir gewählten Lebensweg ermöglichten.

Christina, die die Zeit in Darmstadt hoffentlich nicht nur als eine Zeit der Entbehrungen empfunden hat, und mit der ich die gemeinsame Zukunft gestalten möchte. Ihr sei diese Arbeit gewidmet.



Abstract

The objective of this thesis is the development of a terrain presentation for a synthetic flight guidance system that takes human requirements into account.

The thesis is separated into three major chapters. *Analysis*, *Design* and *Evaluation*.

In the first part of chapter 1 the environment in which a cockpit crew operates is analysed from different points of view after a short description of the environment itself. Special attention will be given to the cognitive aspects concerning conventional flight guidance. Based on this foundation, a new flight guidance concept -the Cavok flight guidance displays- will be described in detail. They have been tested in flight and will be considered as state of the art.

While information requirements and perceptive requirements are excellently realised in the Cavok flight guidance displays, tertiary or cognitive requirements are not sufficiently taken into account. A detailed description of deficiencies concerning mental information processing will be given and will serve as a base for further analysis. The inability of the human to become familiar with this synthetic environment seems to stem from the lack of tertiary information to be taken into account in the development phase of the Cavok flight guidance displays.

In the last part of the *Analysis* chapter, cognitive mapping will be looked at. Current methods of terrain visualisation do not provide the pilot with landmarks and this may be the reason that they have trouble becoming familiar with the environment. Landmarks as the foundation for cognitive mapping seem to be missing since there are no other indications why it should be impossible to get familiar with synthetic environment. Similar examples will be mentioned that indicate that cognitive mapping in virtual worlds is possible. Finally the Cavok flight guidance displays will be analysed under these aspects.

A foundation for the creation of maps, charts and electronic devices will be given at the beginning of the *Design* chapter. After a short description of the cartographic design process a new concept taking primary and secondary as well as tertiary requirements into account will be proposed. This concept changes the geometrical structure of digital terrain data in order to adapt it to human perception and allow cognitive mapping in a synthetic environment. A detailed description of the necessary complex processing will be given. At the end of the *Design* chapter a first indication of perceptive and cognitive as well as technical improvements will be summarised.

In the last chapter, *Evaluation*, the new terrain depiction will be treated. Extensive experiments prove that the terrain conversion process significantly improves the perception and cognition. Necessary time for perception and mental rotation decreased tremendously while the number of hits increased.

Zusammenfassung

Das Ziel dieser Arbeit ist die Entwicklung einer Geländedarstellung für ein synthetisches Flugführungssystem, die den Anforderungen durch den Menschen entspricht. Drei Hauptkapitel bilden die Struktur dieser Arbeit: Analyse, Design und Evaluierung. Im ersten Teil von Kapitel 1 wird die Umgebung, in welcher Piloten arbeiten, kurz beschrieben und unter verschiedenen Gesichtspunkten analysiert. Besondere Beachtung wird dabei die Flugführung unter kognitiven Aspekten finden. Auf dieser Grundlage wird ein neues Flugführungskonzept die -Cavok Flugführungs-displays- im Detail beschrieben. Dieses wurde in Flugversuchen getestet und wird als Stand der Technik betrachtet.

Während primäre Anforderungen an den Informationsbedarf und sekundäre Anforderungen an die Wahrnehmung des Piloten hervorragend erfüllt sind, sind tertiäre oder kognitive Aspekte nicht ausreichend in Betracht gezogen worden. Es erfolgt eine ausführliche Beschreibung der, die mentale Informationsverarbeitung betreffenden Unzulänglichkeiten, die dann als Basis für die anschließende Analyse dienen wird. Es wurde festgestellt, daß das Vertrautwerden mit synthetisch dargestellten Umgebungen sehr schwer fällt oder sogar unmöglich ist. Dies scheint seine Ursache in der Nichtbeachtung tertiärer oder kognitiver Anforderungen während der Entwicklung der Cavok Flugführungsdisplays zu haben.

Im letzten Teil des Kapitels *Analyse* wird das kognitive Kartieren betrachtet. Derzeitige Geländevisualisierungen scheinen keine Landmarken zu enthalten, was die Ursache für das erschwerte Vertrautwerden mit der Umgebung sein könnte. Landmarken, als die Grundlage für kognitives Kartieren, scheinen zu fehlen, da es keine weiteren Anhaltspunkte gibt, weshalb es unmöglich sein sollte mit synthetisch dargestellten Umgebungen vertraut zu werden. Andere Beispiele werden aufgeführt, die darauf hinweisen, daß kognitives Kartieren auch in virtuellen Welten möglich ist. Schließlich werden die Cavok Flugführungsdisplays unter diesen Aspekten analysiert.

Im Kapitel *Design* wird kurz eine Grundlage zur Erstellung von konventionellen und elektronischen Karten gelegt. Nach der Beschreibung des kartographischen Designprozesses wird ein neues Darstellungskonzept vorgestellt, das primäre, sekundäre und tertiäre Anforderungen erfüllt. Bei diesem Konzept wird die geometrische Struktur von digitalen Geländedaten verändert, um sie an die Anforderungen des Menschen, bezüglich Wahrnehmung und kognitiven Kartierens in synthetischen Umgebungen, anzupassen. Dieser komplexe Verarbeitungsprozeß wird im Detail erklärt werden. Am Ende des Kapitels *Design* werden erste Anhaltspunkte für die Verbesserung der Wahrnehmung und der Kognition sowie technischer Aspekte zusammengefaßt.

Im letzten Kapitel *Evaluierung* wird die neue Geländedarstellung bewertet. Ausführliche Versuche bestätigen, daß die Neustrukturierung des Geländes die Wahrnehmung und die Kognition signifikant verbessern. Die notwendige Zeit für die Erkennung und die mentale Rotation der Geländedarstellung sinkt erheblich, während die Anzahl der richtigen Antworten ansteigt.

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Abbreviations

ADI	Attitude and Direction Indicator
AFD	Advanced Flight Display
ATC	Air Traffic Control
CAS	Collision Avoidance System
CAVOK	Ceiling And Visibility OK
CBT	Computer Based Training
CFGD	Cavok Flight Guidance System
CFIT	Controlled Flight Into Terrain
CRT	Cathode Ray Tube
DEM	Digital Elevation Model
DFAD	Digital Feature Alleviation Data
DME	Distance Measuring Equipment
DTED	Digital Terrain Elevation Model
DTM	Digital Terrain Model
DUT	Darmstadt University of Technology
EADI	Electronic Attitude and Direction Indicator
ECAM	Electronic Centralised Aircraft Monitoring
EFR	Extended Flight Rules
EVS	Enhanced Vision System
FLIR	Forward Looking InfraRed
fMRI	Functional Magnetic Resonance Imaging
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPWS	Ground Proximity Warning System
HCA	Human Centred Automation
HCD	Human Centred Design
HDD	Head Down Display
HMD	Helmet Mounted Display
HMI	Human Machine Interface
HSI	Horizontal Situation Indicator
HTML	Hyper Text Mark-up Language
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrumental Meteorological Condition
INS	Inertial Navigation System
LAAS	Local Area Augmentation System

LCD	Liquid Crystal Display
LFT	Lufthansa Flight Training
LOD	Level of Detail
LOWI	Innsbruck Airport
LOWS	Salzburg Airport
MCD	Minimising Collision Damage
MFD	Multi Function Display
MMW	MilliMetre Wave
MPCD	Minimising Post Collision Damage
ND	Navigation Display
NIMH	National Institute of Mental Health
NM	Nautical Miles
NOE	Nap Of the Earth
PET	Positron Emission Tomography
PFD	Primary Flight Display
PSD	Primary Situation Display
PVD	Pseudo Vector Data
RAM	Random Access Memory
RVD	Real Vector Data
SA	Situation Awareness
SID	Standard Instrument Departure
SPSS	Statistical Package for the Social Sciences
SR	Spatial Representation
SSA	Strategic Spatial Awareness
STAR	STandard Arrival Route
SVS	Synthetic Vision System
TCAS	Traffic alert and Collision Avoidance System
TDM	Terrain Depiction Model
TIN	Triangulated Irregular Network
TSA	Tactical Spatial Awareness
TSIN	Triangulated Semi Irregular Network
VDO-L	VDO- Luftfahrtgerätewerk GmbH
VFR	Visual Flight Rules
VMC	Visual Meteorological Condition
VR	Virtual Reality
WGS	World Geodetic Standard

1 Analysis

Vision is our major source of perception. Vision enables the observation of the inhabited area. Hunting and protection from enemies are based on vision. The first mass media was based on vision and enabled publication of know how and ideas. But beside the use of vision for information transfer, vision has always been used for pleasure. Images like paintings touch our emotions through visual perception. They have also been used for information transfer.

While images are static, motion pictures totally changed the quality and use of pictures for information transfer. More complex ideas could be transferred to a broader public and they had another major advantage. Motion pictures have a high information transfer rate.

Computer graphics, used for visualisation of information, offer a new variety of applications. The ability to present information through dynamic images and then to change them interactively has been a mile stone in technical development. While mechanical indicators were limited to showing a single value like temperature or mass flow, the most complex processes can be visualised today.

One application of this is aviation, a dynamic irreversible process that is a challenge even for a skilled and trained crew. Due to the high amount of critical process values this application is predestined for the use of interactive, dynamic information presentation based on computer graphics. The objective is not only to facilitate the work of the cockpit crew and increase safety, but also to increase the operational range limited by weather and high traffic conditions.

In order to profit from this new technology, design has to be based on human requirements instead of technical feasibility. At a first glance, requirements are well known, but information requirements describing the necessary information for a successful task execution are not sufficient. Requirements describing the way of information presentation like symbology and coding for an easy and fast perception are very important as well. So, design has to be adapted to human vision taking physiological limitations into account. These secondary requirements insure the perception of the presented data.

But the perception does not ensure the right interpretation. So tertiary or cognitive requirements also have to be considered when designing a user-friendly human-machine interface.

The objective of this thesis is the development of a visual presentation of terrain, that takes human requirements into account. This presentation shall provide the pilot with easily perceivable tactic as well as strategic information necessary for a safe flight.

1.1 Process Control

Interaction between humans and machines is explained in [Joh93[1]]. Johannsen describes the technical process as a process of changing input and output quantities controlled by the human being and assisted by automation and supporting systems (Figure 1). Typical qualities that are attributed to this human machine system are the type of process and the level of automation. Automation describes the work share between human being and machine concerning the whole process as well as sub-processes. Today, aircraft have a high level of automation. In addition there are assistance systems that support and advise the pilot during his control task. Communication between the technical system and the human being is realised by the **H**uman **M**achine **I**nterface (HMI) that includes input and output devices.

Before classifying technical systems and HMI, human qualities and behaviour should be discussed. The reason for this order is a significant change in designing man machine systems. The human factor approach was very important in the past, creating an environment for the process operator that was much closer to his human requirements. Engineers designed a new vehicle or production plant to solve technical problems. The engineer used his mental model of the process to define procedures. Finally the human factor specialist had to check if this solution was acceptable for the user. Automation was introduced if it was technically feasible and not whether or not it

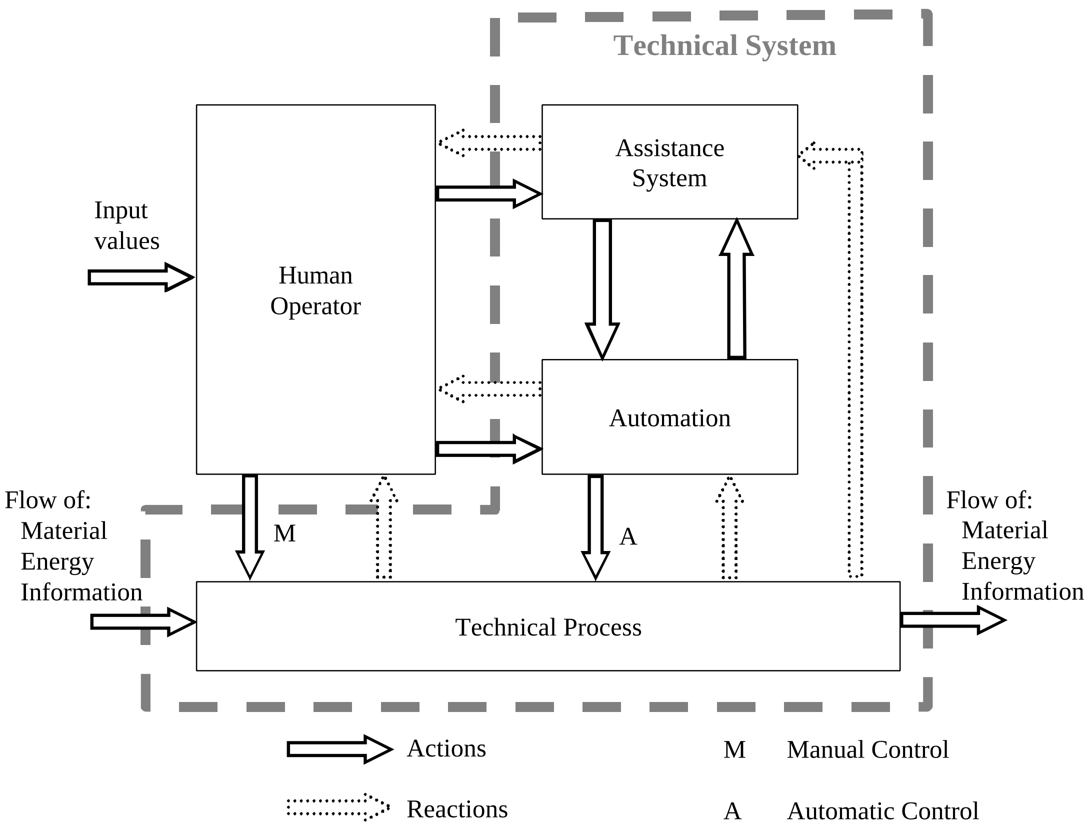


Figure 1 Automated and Assisted Technical System [Joh93]

met user requirements like skills. Today **H**uman **C**entred **A**utomation (HCA) has begun to replace this Technical Centred Automation design approach.

For this reason, psychological aspects will always be investigated first. Technical solutions have to be adapted to human requirements, even if they require a higher design effort or are less cost effective. This hierarchical structure was applied on every chapter of this thesis.

1.1.1 Operator

For the further analysis of the process control and HMI the skills of the human operator are very important. On the one hand, phylogeny describes the process of inter-individual development in the past. Ontogeny on the other hand describes the development of the individual. Due to this individual development it is impossible to describe “the” human operator and his capabilities. Rather these individual qualities will be mentioned in the next chapter because they have significant influence on the operator’s performance when he is involved in a complex process.

Ontogeny

Developmental psychologists are concerned with how and why different aspects of human functioning develop and change across life span. These include physical development, such as changes in height and weight and the acquisition of motor skills; cognitive development, such as changes in thought processes, memory, and language abilities; and personality and social development, such as changes in self-concept, gender identity, and interpersonal relationships[Hil96[2]].

Physical Aspects

Usually physical condition is not as important as physiology or cognition for process controllers. Due to a working place which seldom requires physical effort, physical disabilities have a minor influence on the operator’s performance. However, restrictions in movement of extremities will influence the capability to fulfil a task. Figure 2 shows the ideal performance capability of a human operator. Due to individual circumstances like development, accidents, individual attributes or education these ideal capabilities are not available for every individual. Furthermore, age has a significant influence on physical, physiological and cognitive capabilities which will not be mentioned in detail.

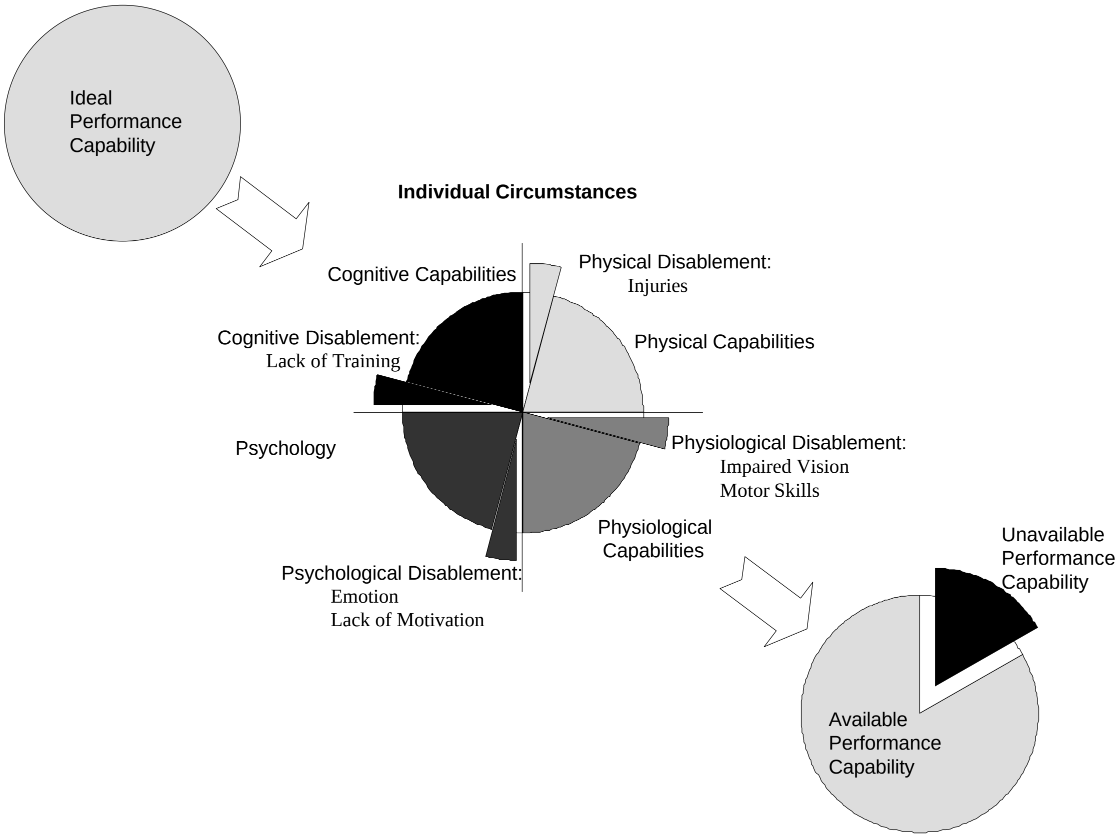


Figure 2 Available Operator Performance Capability

Physiological Aspects

The operator's task is to control a process with respect to predefined limits. These limits are usually abstract limits like current or force which are detected with instruments since the perception of these elements is not supported by human senses. In most cases these parameters are visualised on instruments which require, for example, good vision. Impaired vision, be it innate or be it due to age reduces the physiological capabilities.

Psychological Aspects

Emotion and motivation have significant influence on everyone's performance which distinguishes the human operator from robots. Even if physical and physiological attributes are ideal for a specific individual, lack of motivation can reduce his performance to a minimum.

There are two types of motivation. On the one hand, there is intrinsic or internal motivation which is exclusively based on personal attributes. Motivation based on social hierarchies, status symbols or other experience is usually very strong. Extrinsic or external motivation by rewarding the individual is often limited in duration. Higher salaries or any other kind of reward can motivate humans to fulfil a task better than others.

Cognition

Cognition is a part of psychology and it will be mentioned later. However, it has a major influence on the ability to fulfil a task. Therefore, cognitive capabilities are explicitly shown in Figure 2.

Cognitive capabilities are innate but development, education and training can emphasise and enhance them. Lack of training is a primary cause of errors in process control sometimes resulting in incidents and accidents.

Summary

The human operator is the central figure in process control tasks be he a pilot or an operator of a power plant. His capabilities depend on several individual elements. Interactions between psychology and physiology were not mentioned in this simplified sketch but they exist. Furthermore, any use of drugs like alcohol or opiates will also reduce the available performance capabilities[Yes85[3]]. This indicates that the design of any HMI has to be adapted to the real operator performance instead of idealised values.

1.1.2 Technical System

Technical systems can be classified using different criteria. First they can be classified by the technical application. Other possible classifications are response times, complexity, continuation and level of automation.

Johannsen distinguishes between three main application categories of technical processes. These are production, movement and information which are further separated into technical system classes like vehicles, conveyors and handling tools for the movement category. Within the vehicle class he distinguishes between motor vehicles, rail vehicles, aircraft and ships. A characteristic attribute of aircraft is changing position in space which includes autonomy and the risk of collision with other aircraft or terrain. The following attributes are very important for classifying the process behaviour and the task the operator has to solve.

Complexity and Complication

Complexity describes the quantity of tasks the operator has to work on as Johannsen defines while complication is an attribute of one task describing its difficulty. Multitask processing is typical for aircraft control and results in a high level of complexity. If tasks are coupled the complexity increases even if complication is rather low. Slightly coupled tasks for example are control of yaw and roll axis.

Response Characteristic

Response characteristic is an external parameter that is defined by flight mechanics and control. It is a mathematical description of the dynamic process from the input qualities to the output qualities. High dead times are very difficult to control without any support like quickening tools. The limit of dead time for continuous control is about 0.5 s [Kra98[4]]. Telerobotics is an example of high dead times caused by transmission times. In aircraft control there must be no significant dead times that require higher skills of the pilot or special avionics.

Short response times are essential for aircraft. They require a very high update rate of measured values up to 10/s and low reaction times of the pilot. This results in high workload because the system requires continuous inputs in manual flight. In chapter on automation and assistance we will see that this is a reason for high automation on the control level.

Continuous Process

Process continuity is a typical attribute for moving systems like an aircraft. The most important influence on pilot behaviour is the constant level of activation which results in a pilot becoming tired if the level of automation is too high or too low.

Automation and Assistance

A lot of problems are mentioned concerning useful level of automation, machines authority and final responsibility. Engineers tended to automate functions that can be controlled by the machine in order to support the pilot. Already in 1980 Wiener and Curry pointed out: “The question is no longer whether one or another function can be automated, but, rather, whether it should be!“. Which functions should be automated will be discussed in the following chapter.

In Figure 1, the technical system consists of the technical process, the automation and a supporting system. Instead of calculating a solution or control input and executing it, the supporting system advises the pilot to do something. A typical assistance system with this definition is the Autopilot in flight director mode. Another definition that I will refer to, is shown in Figure 3. Onken distinguishes between automation (conventional or non-cognitive systems) and supporting system (cognitive systems) depending on their cognitive level [Ras88[5]]. The difference between an assistance

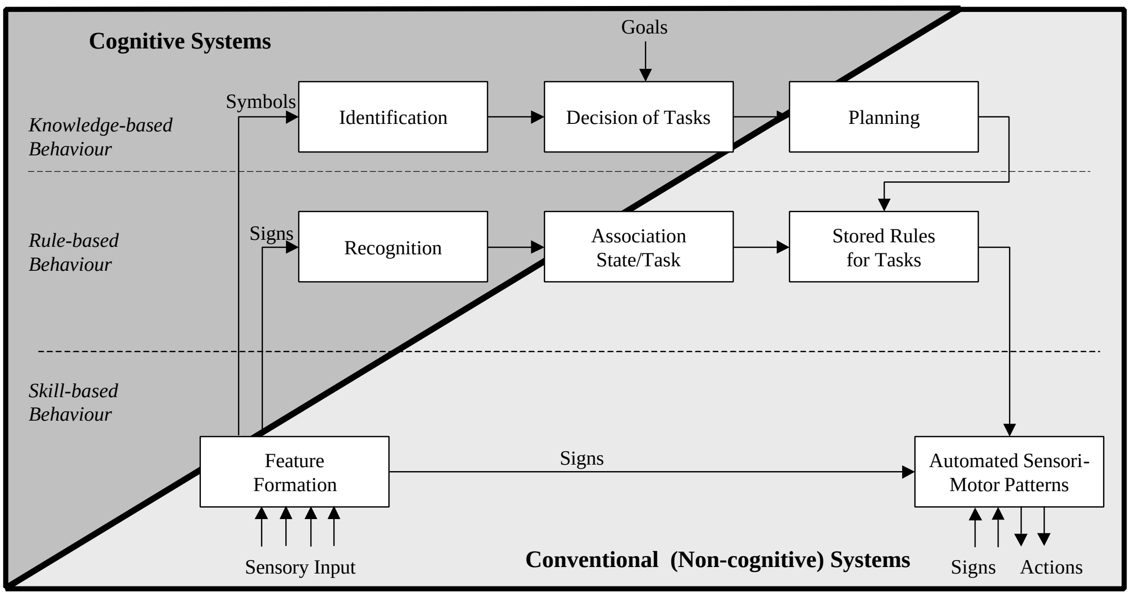


Figure 3 Automation versus Supporting Systems [Onk97[6]]

system and a half automated process, which both support the pilot without execution autonomy, is the support of the operator's cognitive level. While the automation executes relatively simple functions that usually support skill based actions, the assistance system can support rule based or even knowledge based actions and decisions. An equivalent of assistance systems is the expert system which also includes elements of artificial intelligence. In other words, assistance systems are more intelligent automation systems for higher complication.

In addition to the categorisation of different types of automation, the level of automation should be mentioned now. Kraiss [Kra98[4]] describes six levels of automation:

On the third level, for example, the process is manually controlled with limited automation. On the forth level, manual control is limited and the process is under automatic control.

Manual Control	Impossible	Automatic Control
Manual Control	Supported	Automatic Control
Manual Control	Limited	Automatic Control
Manual Control	Limited	Automatic Control
Manual Control	Approved	Automatic Control
Manual Control	Impossible	Automatic Control

Wiener and Curry [Wie80[7]] show the consequences that are affected by different levels of automation. On the one hand, a high level of automation implies boredom, complacency and erosion of competence. On the other hand manual, control results in high workload and fatigue. These effects should be kept in mind for the decision on one level of automation, instead of technical feasibility which is the common criteria.

Tiemann&Borys [Tie95[8]] prooved that interaction between different tasks is very important when designing complex human machine systems. The combination of different tasks like manual control, monitoring or navigation have a significant influence on operator performance. Therefore several tasks which cause high stress as well as several tasks of the same cognitive level should not be combined, since operator stress will increase considerably.

Technical and economical feasibility often depends on frequency of input in comparison with financial effort. Hollnagel [Hol93[9]] points out that tasks of low complexity should not be automated as well as tasks of very high complexity since the effort increases excessively.

Besides the implication of the level of automation like boredom or fatigue, the influence on the human machine interface is most important for the pilots task. In automatic flight the only thing the pilot has to do is monitoring, the observance of critical parameters. Compared to manual flight, there is a significant difference in information requirements. This subject will be mentioned in detail in chapter 1.2.

Technical Performance

Like the circumstances that cause a difference between the ideal and the real performance capability of the operator, there are several circumstances which decrease the machine performance. A new product is usually designed for a predefined operational range. Within a life cycle the environment may change with the development of new communication techniques or safety standards for example. The conceptual capabilities may not be sufficient anymore and may limit the operational range. Mission capability depending on the current status may limit the performance as well. If fuel tanks are large enough for a long distance flight but the aircraft was refuelled for a shorter distance the machine may not be serviceable. Finally the maintenance may also reduce the ideal performance. Cracks in the hull, damages and ageing affect safe load for example (Figure 4).

Summary

The technical process or the machine has individual or specific attributes. These attributes have a strong influence on the operator’s task. Technical performance is not ideal as the design engineer might estimate from his conceptual design.. Influences like inadequate system design due to non human centred design will further reduce the operator’s performance. The HMI the interface between a real operator and a real machine will be addressed in the next sub-chapter

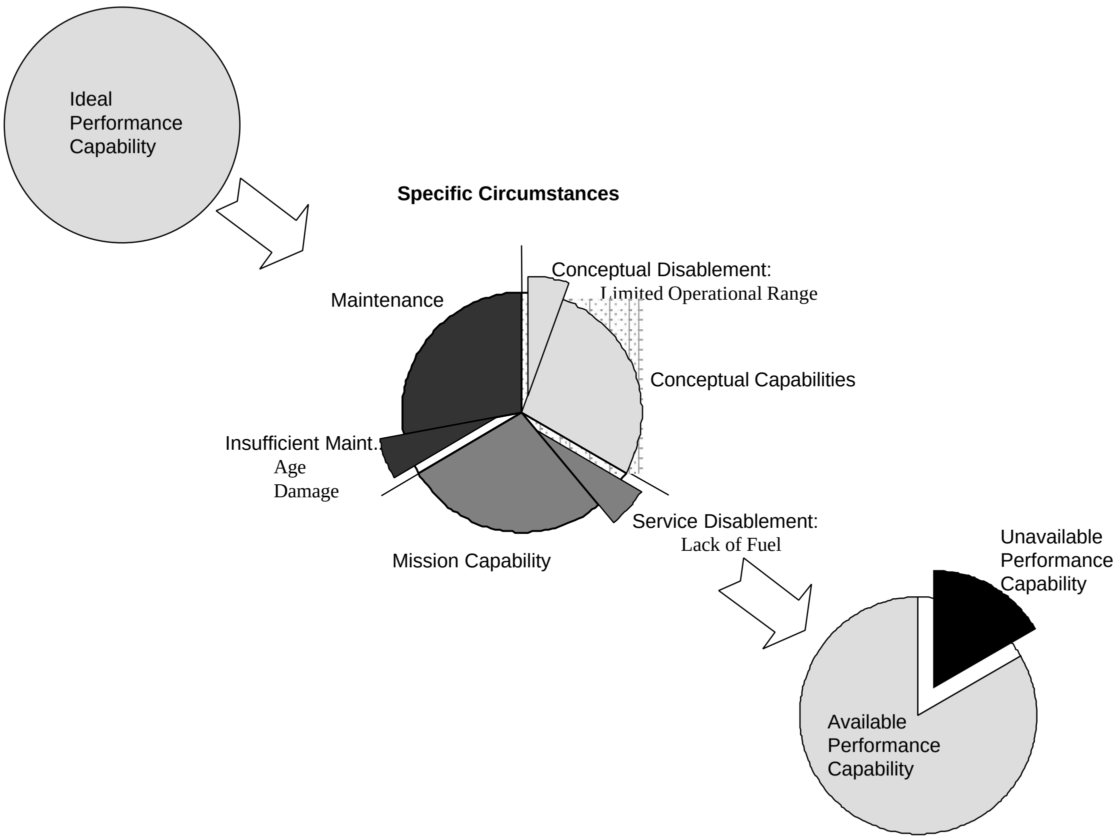


Figure 4 Available Machine Performance Capability

1.1.3 Human Machine Interface

The human operator's as well as the technical system's attributes were described and classified as independent components of the man-machine system. Their individual or specific capabilities were mentioned, however the system has to be seen in total. On the one hand this interface informs the operator about the current system status and enables system awareness. On the other hand the interface allows operator input be it goal defining values or manual control inputs. Interfaces are part of the technical system and thus called output devices if the technical system gives information to the operator. Information is transferred through the input device from the operator to the technical system. The design of the HMI has significant influence on fulfilling the task. Even, if the operator is in good condition and the system is serviceable, a poorly designed interface may make it impossible to perform a task adequately. Pilot caused accidents like **C**ontrolled **F**light **I**nto **T**errain (CFIT) are a clear indication of a bad interface that is not designed according to human factors as well as cognitive engineering aspects. In the next chapters input devices will be classified and described briefly and major attention will be given to the output device.

Input Device

The input device serves as the necessary interface between the operator and the system for user motivated inputs. For the realisation of decisions based on a previous mental process, the operator transfers information about his goal or goal oriented tactical objectives. Usually this input is based on body movements. The strong separation between input and output devices is integrated in some devices. Touch screens for example are input devices but the user may also be informed about his input or changing system status by the same device.

Schmidtke classifies input devices concerning the type of [Rüh93[10]]:

Input

Movement

Technical principle

Dimensions

Output Device

The most common device especially in commercial aircraft is the **H**ead-**D**own **D**isplay (HDD). Until 1995, stroke writing **C**athode **R**ay **T**ubes (CRT) were state of the art. Modern aircraft like the B777 or A340-600 are equipped with conventional **L**iquid **C**rystal **D**isplays (LCD).

The **H**ead-**U**p **D**isplay, or HUD, used in many military aircraft is an extension of the conventional **A**ttitude **D**isplay **I**ndicator (ADI) or artificial horizon. Like the ADI, the HUD presents attitude information, but this information is projected onto a transparent screen behind the windshield or onto the windshield itself in the pilot's line of sight. It is often accompanied by the projection of related instrument information (e.g. airspeed, altitude). The intended purpose of such a projection is, of course, to allow the pilot to take information from the HUD instruments without taking his eyes off the outside scene [Wie88[11]]. A synthetic runway as well as the glide slope visualised as a “tunnel in the sky” on a HUD is the most effective use of a **S**ynthetic **V**ision **S**ystem (SVS)[Hel95[12]]. The disadvantage of HUDs is the cluttering of the view of the outside world resulting in the need to “learn to look through it”[Kai96[13]].

1.2 Flight Guidance

Baron [Bar88[14]] characterised the pilots task like this: Flying an airplane, be it for military, commercial, or purely personal reasons, is a goal-oriented human activity. Inevitably, it involves deciding on routes and flight paths to follow, selecting appropriate motion parameters (course and speed) for guiding the aircraft along those routes, and controlling the aircraft to maintain it on the chosen paths in a safe and stable fashion. All this must be accomplished by the pilot under constraints imposed by both the limits of aircraft capability and environmental conditions (weather, terrain, other traffic, etc.) and while performing other supportive tasks such as system monitoring and communication. This is, fundamentally, a very complex task. The manner in which it is, or must be, accomplished by the pilot is to a great extent determined by the motion characteristics of the aircraft itself. It is also significantly dependent on other factors such as the pilot–vehicle interface and the degree and character of automation.

Modern aircraft changed the pilot’s working environment significantly. Aircraft stabilisation is fully automated and the task of manually controlling the aircraft is necessary during a minute period of the flight. Today pilots have to switch off the autopilot regularly so that they do not lose the skill of controlling an aircraft. Supervisory control is the pilot’s task, which means he is monitoring the system. He is a manager, on the one hand, who selects the required altitude if the system operates properly. On the other hand, he is the pilot who has to manually override the automation in an abnormal situation.

Of course the pilot is not and should not be a protagonist as described above. In modern aircraft the two crew member cockpit consists of the captain and the first officer who may share tasks. Technicians and navigators were replaced by automation which increased the complexity of the pilot’s task significantly.

Remark:

The common expression situation awareness will be mentioned frequently and will be used in this sense:

Situational **A**wareness (SA) is the pilot's mental picture of the aircraft relative to its more-dimensional operational environment, including navigation and terrain, the configuration and safe flight of the aircraft, and the health and mode of operation of its systems.

1.3 Spatial Information in Aerospace Operations

1.3.1 History of Spatial Instruments

The advanced electronic displays and controls in modern transport aircraft reflect over a century of development. The evolution has taken place not in order to make the flight deck more comfortable or convenient as a workplace but as a result of two major pressures – safety and economics - between which there is an inevitable interaction.

As air transport has become a more popular means of travelling and as aircraft have become larger under economic pressure. There have been more victims per accident and the public and litigation industry have paid greater attention to air disasters. References were often made to incorrectly operated controls, such as flap instead of landing gear, and faulty or failed instruments. At the same time, aircraft performance was increasing, again under economic pressures, and this required more information input from the pilot, more sophisticated controls and more complex displays to permit safe operation.

The earliest form of flight instrument, the barometer used in balloons from the 18th Century, remains the basis of today's pressure altimeters. It was not until the advent of the need to fly without visual references – blind-flying as it was called – about 1930, that serious attention was paid to the development of displays. Earlier displays ranged from the piece of string used by the Wright brothers as a slip indicator to conventional engine RPM indicators.

The breakthrough which permitted this new form of flying in both military and civil aviation, came from the development of a usable gyroscope which could be applied in the form of an artificial horizon. While today's pressure altimeters owe their origin to the barometers used in balloons, the sophisticated gyro-stabilised platforms which form the basis of modern flight guidance systems can trace their origins to the primitive gyroscopes in the artificial horizons of the inter-war years.

With the development of electronics, servo-driven instruments became possible in the 1950s. This permitted a very notable improvement in instrument design as the sensor could be remotely located away from the instrument.

One other technical development that has had a major impact on displays is the CRT. This was already in service in some military aircraft in the early 1940s but it took another quarter of a century before it became available for display of primary flight information.

Aviation electronics, or avionics, have been one of the necessary pillars upon which progress has been built. Another, regrettably frequently neglected element, has been ergonomics. Yet, it was too often considered adequate to have information available on the flight deck without considering adequately how this was to be sensed and processed by the crew member. Aviation, of course, is not the only example of where this has been neglected; it is apparent throughout industry including nuclear power stations where inappropriate human control can be as catastrophic as in air transport.

Man as an operator is adaptable and this adaptability often masks display and control deficiencies which nevertheless continue to trap the unfortunate or unwary. However, several important Human Factors studies have improved instrument development though the findings of such works have not always been properly applied. By the 1960s, numerous studies were being conducted on electronic displays. Research on the Human Factors of CRTs expanded rapidly so that by the 1980s, it became possible to publish extensive reviews of current knowledge of ergonomic aspects of visual display terminals.

It was in the early 1980s that the all-digital A310 and Boeing 757/767 introduced CRT flight displays in civil aviation and this marked the watershed in the evolution of the glass-cockpit. While the technology employed in the displays was not significantly different, conceptually the A310 and A300-600 displays were more advanced than those of the Boeing aircraft. Boeing used **E**lectronic **A**ttitude **D**irector **I**ndicator (EADI), which has display details similar to the electromechanical ADI which it replaced. On the other hand Airbus took advantage of the research on the Weybridge **A**dvanced **F**light **D**eck (AFD).

They chose to introduce the **P**rimary **F**light **D**isplay (PFD) which incorporated the main airspeed indication, selected altitude and deviation and full flight mode annunciation but could, on selection, be changed to a flight path vector display (Figure 5).

There was little difference between the CRT **N**avigation **D**isplay (ND) on these aircraft, which provided a map mode, a reproduction of the conventional **H**orizontal **S**ituation **I**ndicator (HSI) and superimposition of weather radar (Figure 6).[Haw87[15]]

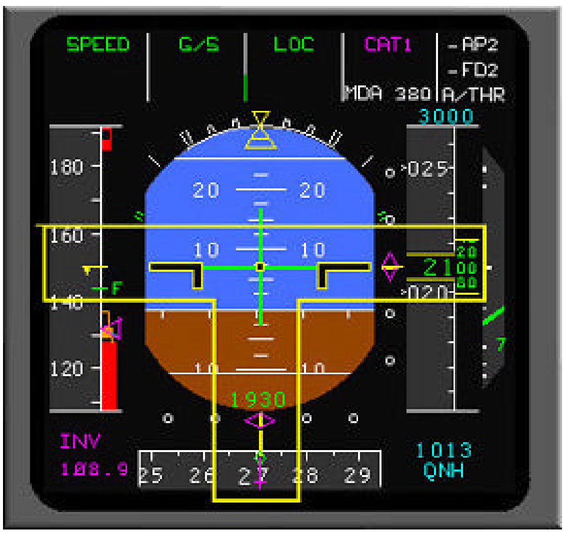


Figure 5 Primary Flight Display

Figure 6 Navigation Display

1.3.2 Inadequate Spatial Situation Awareness

Our everyday experience with the world around us reflects the world's scale and complexity. The physical area that we can perceive directly at any moment is restricted by the spatial range of our senses and the information sources and barriers that surround us. In comparison to the earth's surface, this perceived area is minute[Dow77[16]].

1.3.2.1 Natural and Coded Information

The pilot's job is to acquire a lot of information and combine it into a complex internal representation. It is a kind of multi-media puzzle in a time critical environment. The types of information available for the pilot may be distinguished into natural and coded information. Natural and coded indicates the way the information is perceived by mental processes. For example, humans estimate the distance to an object for example from perspective, parallax and experience. In contrast, the distance measured by a Navigation-aid like a **D**istance **M**easuring **E**quipment (DME) is presented in nautical miles. On the one hand the pilot has to learn the arbitrary definition of the dimension of 1 NM, on the other hand he has to read the digital value on his instruments. The creation of an internal representation of the current position is totally different depending on the available information. While natural information can be perceived intuitively and thus very quickly, coded information has to be decoded and analysed.

For some parts of this puzzle, the way of presentation is classified here and compared for **V**isual **M**eteorological **C**onditions (VMC) and **I**nstrumental **M**eteorological **C**onditions (IMC). (Figure 7). If you look at the perception of aircraft attitude in both the VMC and the IMC, you have natural information in VMC by looking out of the window and perceiving the horizon and also in IMC, since the artificial horizon is the only instrument that has a natural pilot interface.

	Visual Flight	Instrument Flight
A/C Attitude	natural	natural
A/C Position	natural	coded
Flight Path	coded	coded
Terrain	natural	
Traffic	natural	coded

Figure 7 Information Coding

In contrast to this, aircraft position and traffic surveillance are natural in VMC and coded in IMC. The pilot gets digital information about altitude or vertical separation to the intruder. As mentioned above, decoding is necessary which increases the mental workload and the probability of errors.

The examples mentioned above should illustrate the deficiency in the way of information presentation. In addition to this poor way of presentation, terrain is natural in VMC and not even presented in IMC. This is an enormous lack of information that is a major cause of accidents. If the pilot follows his procedures he probably will not have an accident even if he has no sufficient SA. But once the pilot makes a mistake the system cannot support him on finding the way back to the required flight-path and continuing the procedure. Mistakes are the only way to learn and the capability to learn is the advantage the pilot has over the automation. Thus, it is very important to have an error tolerant system. This includes presentation of limits and reversibility of actions. Condensed: a **kind environment** [Ras88].

Summary: It is very important to give the pilot the information to maintain SA in situations of high workload like in adverse weather conditions and to give it in a natural and intuitive way to ensure a fast perception and integration into his internal representation.

1.3.2.2 Controlled Flight into Terrain

Air travel is one of the safest means of modern mass transportation with an average of 3 accidents per million departures over the past ten years or 2 accidents per million flight hours [Ott97[17]]. However there has been and continues to be a steady increase of departures of about 5 to 7% with a total amount of 17.8 million annual departures of western built aircraft in 1997 (Figure 8).

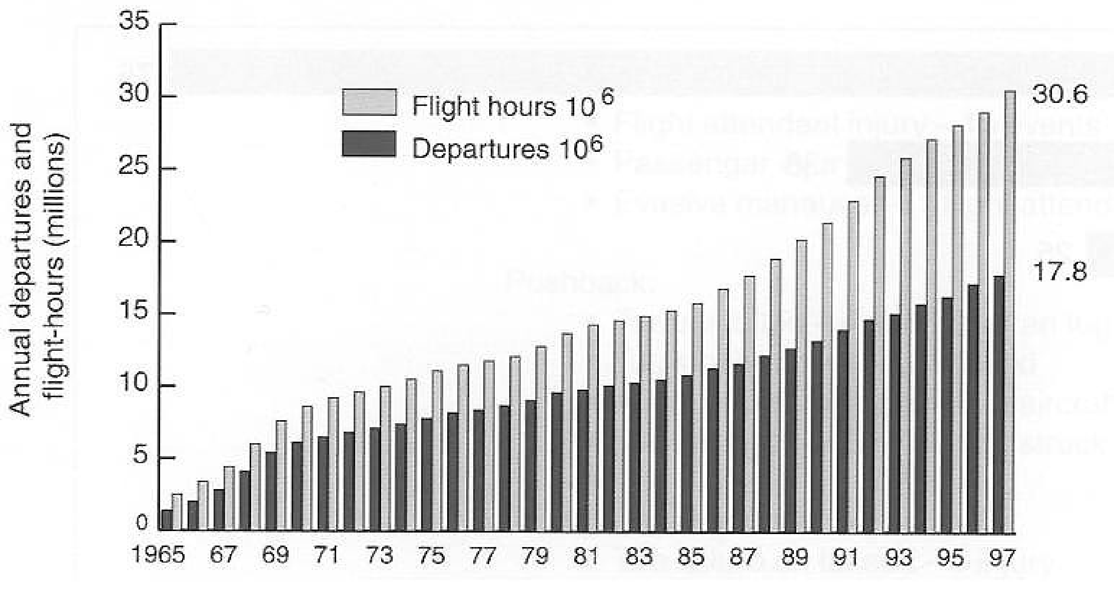


Figure 8 World Wide Operations of Jet Airplanes 1965-1997 [Boe98[18]]

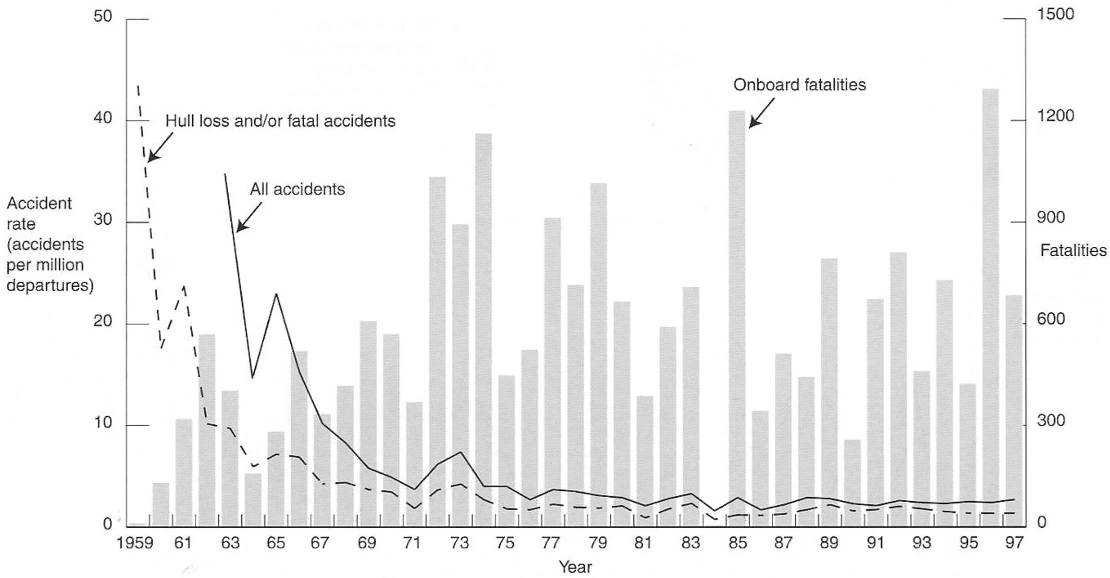


Figure 9 Accident Rates and Fatalities by Year [Boe98]

Technical progress improving the airframe and engines reduced accident rates of more than 35 per million departures in 1963 by more than factor 10 within ten years. However, accidents rates could not be reduced ever since (Figure 9). This implies an absolute increase of accidents and fatalities with doubling rates of 10 to 20 years. In light of these statistics and with the objective to further increase safety, the causes of accidents have to be analysed.

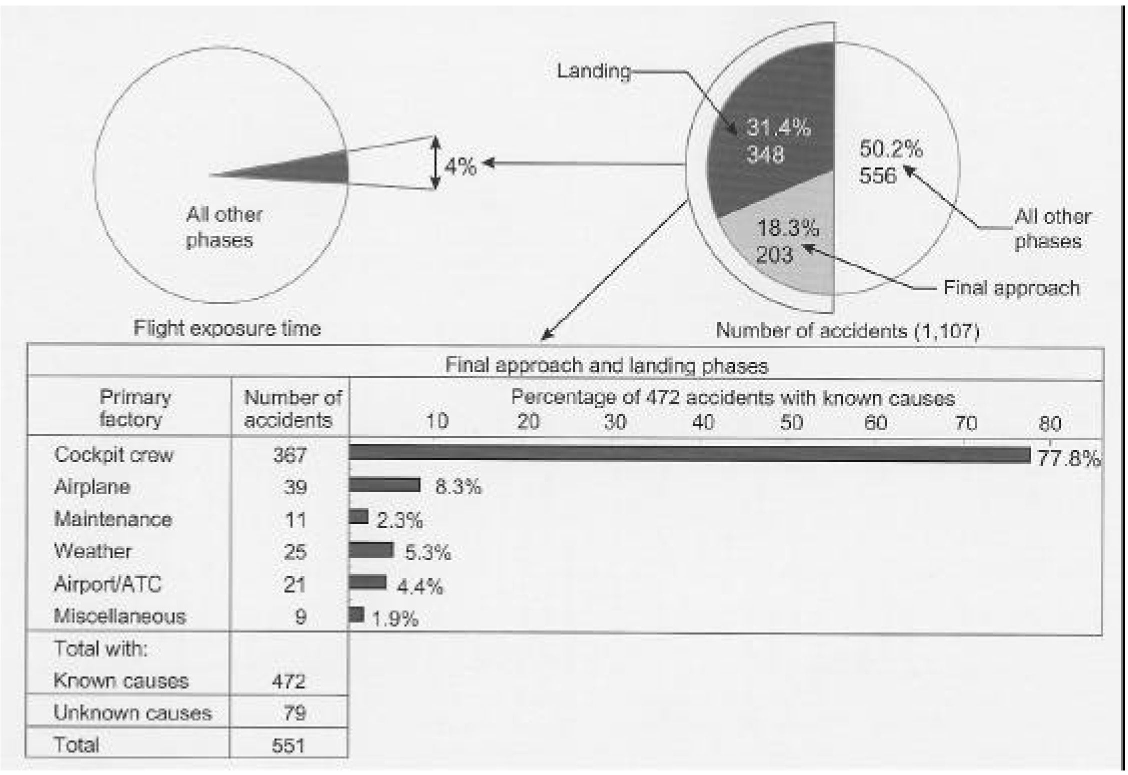


Figure 10 Critical Time and Cause of all Accidents from 1959 to 1996 [Boe97[19]]

About 50% of all accidents occur during final approach and landing while the exposure time of this flight phase is about 4% of the flight. This is the first indication of a strong imbalance in workload for the pilot. Boeing analysed accident causes in these flight phases and evaluated the cockpit crew to a primary factor in about 78% of these accidents(Figure 10).

Considering the extensive process of pilot selection under psychological and physical aspects this result is surprising. Education including courses in technical basics, large-scale aircraft ratings and simulator training as well as refresher courses seems to be insufficient, although education costs for the airline are immense.

Pilots are not able to fulfil their task safely in any conditions because their working place and environment seems to be inadequate. So the question is whether the cockpit crew or the responsible design office should be blamed. Human factor has become the vogue word in aviation as well as in other highly automated processes. The interaction of the human being and the machine has to be improved significantly. Since the human being is able to adapt his behaviour to the environment, the effort spent on **H**uman **C**entred **D**esign (HCD) was insufficient.

Accident statistics suggest that CFIT remains one of the leading categories of air carrier accidents [FSD96[20]]. The Boeing accident statistics (Figure 11) shows that 36 out of 126 fatal accidents are classified as CFIT accidents. Another 31 are due to loss of control in flight.

According to one often quoted definition, a CFIT accident is when an otherwise serviceable aircraft, under the control of the crew, is flown (unintentionally) into terrain, obstacles or water, and the crew is not aware of the impending collision [Wie77[21]].

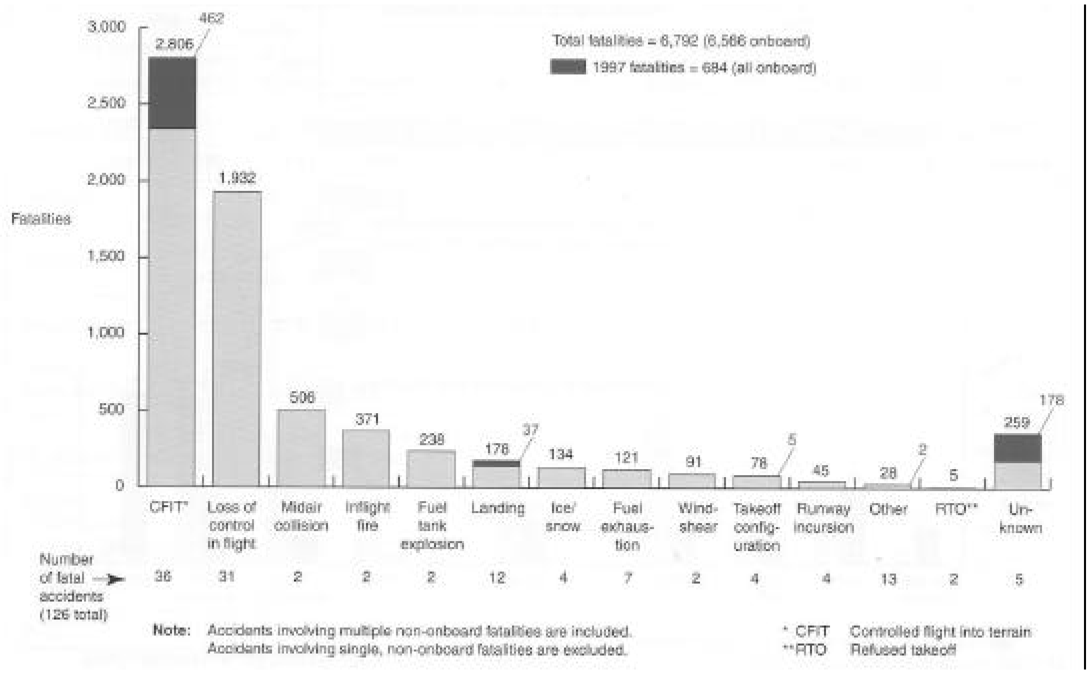


Figure 11 Fatalities by Accident Categories 1988-1997 [Boe98]

There are no causal factors that are inherently specific to CFIT. However there are human factors that contribute to CFIT accidents and incidents.

Human factors associated with CFIT accidents usually include errors, violations, and mistakes by operational personnel – both aircrew and **A**ir **T**raffic **C**ontrol (ATC). These human factors generally have immediate consequences.

Here are some common factors that contribute to CFIT accidents. These factors, which tend to be cumulative in effect, include both human and other factors[Car96[22]]:

- Vertical profile errors
- Weather
- Poor pilot response
- Aircrew complacency
- ATC communications
- Failure to monitor or manage the autoflight system

Over the years more than two thirds of all CFIT accidents have been the result of altitude error or lack of vertical SA. The causes include lack of pilot understanding of ATC clearances, misreading approach charts, or poor altimeter-setting procedures. Many of these flights were on course, just at very low altitudes.

Weather and visibility usually play a role in CFIT accidents. Low ceilings, poor visibility, or night operations are almost always present when a CFIT accident takes place. How the flight crew deals with these occurrences depends on how well they are trained, how closely they adhere to cockpit procedures, and how well the approach charts are designed. CFIT accidents generally occur in instrument weather conditions or under visual conditions at night and are most likely the result of a failure to adhere to a published approach procedure. 87% of CFIT accidents are in IMC, about 90% are within 15 NM from the airport, and in 40% of CFIT accidents, there is no significant terrain elevation [Hel97[23]]. The prime factor in this category is a descent below minimums during an instrument approach, which causes the aircraft to contact the ground before it reaches the runway. There are several reasons for the flight crew to descend below minimums. One is their lack of positional awareness. They may know the aircraft's position, but be unsure of the navigational aid. Or, they may know the position of the navigational aid, but be unsure of the aircraft position. Sometimes, the flight crew does not know either of these things and is totally lost – but can't or won't acknowledge it.

1.3.3 Safety Concepts for the reduction of CFIT accidents

One of the aviation industry's major safety concerns is the flying of perfectly good aircraft into the ground. Which concepts are able to reduce hull losses and fatalities?

A typical classification, as it is known from car constructors, is the separation into active and passive safety concepts (Figure 12).

Active safety is pre-impact safety and passive safety is post-impact safety. Within passive safety we have to distinguish **M**inimising **P**ost **C**ollision **D**amage (MPCD) and

Minimising **C**ollision **D**amage (MCD). MPCD is the last chance to reduce passenger injuries when the vehicle has crashed and is already burning for example. The installation of fire extinguishing systems is in this case the final thing a constructor can do for the user.

MCD is a concept situated between impact and MPCD. The vehicle is impacting, but the chance for passengers to survive can be increased by the introduction of shock absorbers or airbag systems.

These concepts of post impact safety are very important, but a significant increase of safety can only be reached by active concepts.

As mentioned above, loss of situation awareness is the major cause of CFIT accidents. Being unaware of their situation the crew are also unaware of their current unawareness. Wickens described the situation like this[Wic94[24]]:

“Many pilots don’t know what they don’t know, and don’t know that they don’t know it.“

The pilot has a lot of information but he is not able to combine it into a sufficient internal representation. Now after he has lost SA there are three possibilities:

1. He is lucky and regains SA before the situation becomes crucial.
2. He crashes.
3. A Ground Proximity Warning System will alert and in general advise him how to solve the problem.

In the last two decades safety was increased tremendously by the introduction of **C**ollision **A**voidance **S**ystems (CAS). In the 1970s, **G**round **P**roximity **W**arning **S**ystem (GPWS) and, in the 1980s the **T**raffic alert and **C**ollision **A**voidance **S**ystem (TCAS) were introduced. These airborne systems control the actual flight path concerning terrain separation and proximity rate and alert the pilot if there is the risk of an impact. Besides issuing alerts like “Traffic“ or “Terrain“, these tools also generate a problem solving advisory.

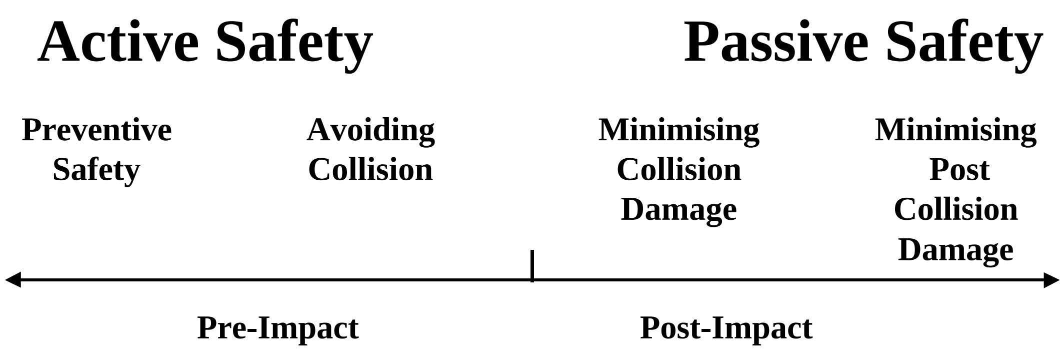


Figure 12 Safety Concepts

But these tools only help the pilot to survive, not to regain SA. How can we describe the pilots cognitive situation in case of an alert?

"The pilot doesn't know what he does not know, but he knows that he doesn't know something."

At this point, he is very confused and needs more help than simply the way to avoid the next mountain. But how can a complex situation like this be presented to the pilot?

The 3D Flight Guidance Display presented in this thesis tries to increase safety one step before the loss of situation awareness**. Preventive Safety Concepts** try to keep the pilot in the loop. He is supported in creating and updating his internal representation with a presentation of the required information in an intuitive way. If this can be achieved, a CAS system and passive concepts will never be vital [Hel97].

1.3.4 Pictorial Displays

Why should we invent arbitrary discrete symbols which have to be memorised when the real world provides us with integrated visual cues? Man cannot integrate multiple factors very well but since he is a product of the real world environment he is an excellent differentiator.

The objective of airborne instrumentation is to overcome the human's limitation in sensation and perception. Besides airspeed, which is not perceivable with regards to aerodynamic limits, the position of the vehicle relative to the spatial environment is especially vital. In adverse weather conditions, spatial orientation and navigation is impossible without ADI and HSI. From the engineer's point of view, this information measured with the help of radio navigation and **I**nertial **N**avigation **S**ystem (INS) is sufficient for a safe and adequate movement. However, from the psychological point of view these values are unnatural and demand decoding and integration into an internal representation. How can this mental process be aided?

The spatial instruments should present an image the pilot is used to in good weather conditions. Of course this is not possible, but there are two approaches that come quite close to this objective.

First, the visual limitations can be bypassed by sensors like radar, infrared and other sensors that operate like the human eye. These systems are called **E**nhanced **V**ision **S**ystem (EVS).

Secondly, the outside view can be synthetically generated vision displayed on graphic computers called SVS.

Enhanced Vision Systems

EVS use real time sensor images from a limited field of view mostly in front of the vehicle. Typical frequency ranges are in electromagnetic radiation, which have an advantageous behaviour concerning humidity in the transmission media. Compared to the optical frequency range that is very limited in bad weather conditions, influences by fog or rain drops are less for EVS. On the one hand image generation may be based on natural radiation detected by passive systems. Active systems, on the other hand, emit radiation and detect its electromagnetic reflections. Technical details can be found in [Kle93[25]] and will not be mentioned here. Instead qualities and problems concerning the HMI based on this concept will be analysed.

Besides a very detailed depiction, up-to-date information is the advantage of all kinds of sensor systems. Objects on the runway and unexpected obstacles in **N**ap **o**f the **E**arth (NOE) operations are especially detectable. Minimum resolution is defined by the “visual” range of the sensor, the resolution of the display and the decision height resulting in about 0.1 degree. Frame rates and latency are major criteria for the usability of sensor systems. Harris [Har92[26]] evaluated that 11hz is the lower limit for frame rates of an operational system. Lower frame rates result in significant loss of performance (over speed, high vertical speeds, displaced point of impact, pilot induced oscillations). Similar problems were detected if latency rises above 200ms forcing higher workload. In general, these problems are more difficult to solve for active systems.

Object or pattern recognition differs distinctly from natural perception in visual range, since reflection and emission have a different physical characteristic. Emission characteristic of passive systems is dependent on differences in temperature. High temperature gradients are detected and visualised as high contrasts. Temperature changes during 24 hours cause crossover effects when the thermal characteristic changes. The inversion of temperature gradients happens twice a day. While concrete is hot and forest or vegetation is cold in daylight conditions it is vice versa at night. Hammer mentioned that the typical times of inversion are about 8 a.m. and 21 p.m. when the contrast changes and is temporarily zero [Ham96[27]].

Parallaxes and angular errors are general problems of EVS. They are caused by the physical separation of the sensor and the pilot’s eye. Images presented on the Head Up Display especially make the pilot detect this discrepancy since natural and sensor images are not perfectly matching.

One important disadvantage is the pixel characteristic of the image. Objects detected by the sensor are implicitly integrated in the video image and may be extracted as distinct objects by the human. However, the system itself is not able to extract objects like obstacles from the detected image. This object extraction requires tremendous computational effort and is currently not possible for real time applications. The advantage of object extraction is, for example, the possibility of database matching or emphasising of runway borders. Today this deficiency requires high mental effort from the pilot since sensor images are often monochrome and usually flicker.

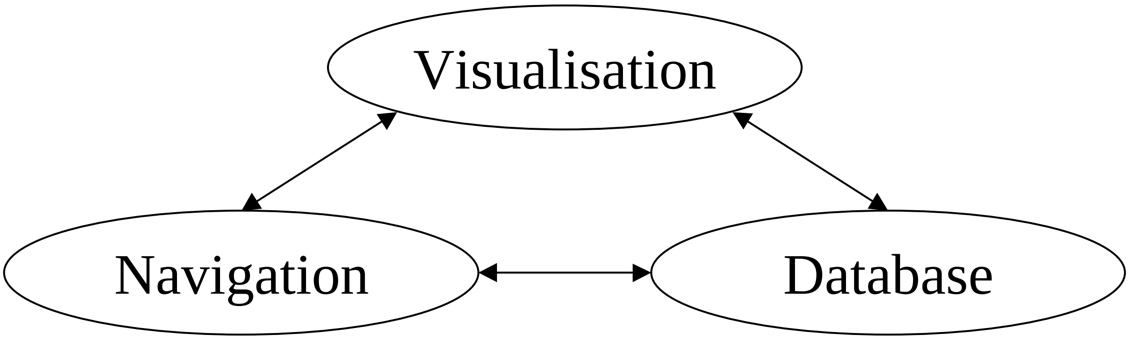


Figure 13 Components of a Synthetic Vision System

Synthetic Vision Systems

Computer generated images offer new possibilities of information presentation and information coding. An offline generated database, a graphics computer capable of generating a 3D image from this database, and a precise navigation are the three components of a synthetic vision system[Kra98[28]].

Database

The database usually consists of different layers, flight critical information like NAV-Aids, airways and **I**nstrument **L**anding **S**ystem (ILS) information that is already available today, and obstacle, runway and taxiline information that will be available in the near future[Pfi97[29]]. Terrain as the major information for terrain avoidance is also available today. With the help of satellites a digital elevation model of the world has been generated. Equidistant elevation data are available at different levels of resolution and accuracy. They are stored in an equidistant matrix of X,Y,Z coordinates with a resolution of 30" (about 1km) and tiled in 1°x1° in central Europe for example. This data format has advantages because of the amount of mass data to be stored. Since the lattice is equidistant, the north and east position only has to be stored for the first point (usually the south west corner). Thus, data can be reduced to one third compared to an array of X,Y,Z values. However, the database has to be topical and based on the same geographic reference system as the high precision navigation. Today the **W**orld **G**eodetic **S**tandard (WGS84) defines a standard ellipsoid on which satellite navigation as well as Digital Elevation Models (DEM) are based[SMR97[30]].

Navigation

Since applications in aviation require high safety standards, the navigation unit has to satisfy these in terms of accuracy as well as in terms of reliability and integrity. For navigation purposes, integrity is defined as the ability of a system to provide timely warnings to users of when the system should not be used [Gra97[31]]. Existing navigation systems are already capable of automatic landing procedures under CAT III condition, which has become routine in the every day air traffic. The navigation system introduced by Pfister has the potential to achieve this performance without standard Nav-aids (e.g. ILS, DME etc.) but with sensors which are available on modern commercial aircraft[Pfi97[29]]. In addition, the **G**lobal **N**avigation **S**atellite **S**ystem

(GNSS) is integrated into the whole system. The development of GNSS has raised great expectations for the use of navigation in various applications. Enhanced by **L**ocal **A**rea **A**ugmentation **S**ystem (LAAS) together with cinematic carrier phase tracking, an accuracy with the remaining error in the range of 10^{-1}m is feasible for dynamic applications. However in high precision and safety critical aviation applications, GNSS shows severe deficiencies in the following areas:

1. Continuity: satellite masking can cause outage of GNSS
2. Availability: channel jamming or certain interference phenomena in some areas can also cause outage of GNSS
3. Integrity: multi-path, cycle slips and incorrect satellite data can corrupt the received data and result in position errors up to 100m.

With respect to these problems, a board autonomous sensor like an inertial navigation unit has to be integrated into the system. This platform is the core of the system because of its robustness and the stationary signal characteristics it provides. Every malfunction will be detected by the board control, and for fail-op requirements, a redundant set of three such units can be integrated.

Most modern commercial aircraft are already equipped with such a redundant set because of the reliability of INS. Therefore the navigation concept proposed by Pfister [Pfi97[29]] can be applied to these aircraft without major changes in the sensor assembly board.

Visualisation

The third component of the SVS is the image generation or visualisation. With the actual sensor data for position and attitude and the database information on terrain elevation, a synthetic picture of the present situation can be generated. This synthetic picture is updated with at least 10 Hz and gives the pilot a dynamic impression of his current situation. If the visualisation is used for the final approach higher update rates are necessary and latency problems appear.

Most of the graphic engines generate triangles from three points given in Cartesian coordinates X,Y,Z. Those points are transformed from 3D to 2D based on any perspective rule. Flat shading results in an opaque triangle, while gouraud shading allows homogeneous shading interpolated between the three colours defined for the points. A terrain triangle based on elevation colour coding for example is rendered by the graphic engine from three X,Y,Z values and three R,G,B values.

The SVS has significant advantages compared to any kind of EVS. First, the generated synthetic image is independent from meteorological conditions. While both systems compensate for the deficiency of vision due to meteorological conditions, the EVS is still limited in operation due to sensor performance.

The major advantage of an SVS is the possibility of selecting and deselecting information depending on user requirements. Today the EVS pixel based sensor image allows only limited online data extraction. Visualisation of database information allows it to present information that is actually required and emphasise it with colour or interaction for example. This property allows the adaptation of the presented information to the requirements of human perception and cognition. Especially interpretation can be simplified in order to reduce learning and training effort.

And there is another advantage of SVS: while the EVS presents a limited field of view predefined by the sensor, a synthetic vision system can present any field of view as well as any cartographic presentation known from maps and charts. This allows the SVS to be applied not only as a tool for short term or tactical system like the enhanced vision system but also as a mid and long term or strategic system. This ability ensures situation awareness independent from meteorological conditions, by the means of system design based on human requirements.

1.3.4.1 Cavok Flight Guidance Displays

Device oriented Cockpit
Cockpits in pre-glass cockpit era became more and more crowded with each new technology requiring a separate input and output device. Flight deck designers tried to minimise separation between those under human factor aspects. But the problem of “One Information One Device” could not be solved because of the limited functionality of mechanical instruments.

The glass cockpit generation enables the functional integration of mechanical instruments into one display device. While display size in former cockpits was limited by technical constraints, very small symbology may be visualised now. Today, only human factor aspects limit the size and amount of information depicted on one display format. Organising correlating information like engine data or hydraulics in layers is another important advantage of modern glass cockpits. The **E**lectronic **C**entral **A**ircraft **M**onitor (ECAM), for example, combines information depiction on one screen and makes modern cockpits look tidy [Nit97[32]].

Six identical screens increase redundancy in case of display failure, since every screen signal can be connected with every screen. Although this allows a flexible arrangement of formats, this flexibility is not used today.

Desktop oriented Cockpit
Foltis [Fol98[33]] proposed a *desktop oriented cockpit* design. The idea is to drag and drop display formats from screen to screen depending on the pilot’s present task or focus of attention. If the pilot then changes the flight plan on FMS, he can pull the necessary format into his central field of activity. For checking weather conditions, he may switch to the weather radar depiction as well as to the satellite images transmitted via data link. One ergonomic input device in front of the pilot could replace several minimised devices all over the cockpit.

Which screen is appropriate for these actions? If square screens will be replaced by rectangular ones in upright format, the conventional PFD could be placed above the navigation display on a single screen. This display should be quasi non-interactive since all basic information is combined here and should be available at all times and for all situations. Supplemented by the engine information N_1, this single format is sufficient for basic airmanship. Figure 14 shows a proposal for a **P**rimary **S**ituation **D**isplay (PSD).

Now the second display in the main field of activity is available as a desktop. Soft buttons in the headline support interactions like selection of sub formats [Kel97[34]]. Figure 15 illustrates one format of the **M**ulti **F**unction **D**isplay (MFD).

Display Philosophy

The next chapters will focus on the PSD consisting of the Cavok Primary Flight and Navigation Display developed at Darmstadt University of Technology. The 3D Flight Guidance Display proposed here is based on a contact analogue synthetic vision system. There is an "inside out view" of the actual situation called the PFD and a parallel projection including the same objects called ND. Displayed objects are database information, virtual objects like flight path, flight path prediction and online information like flight plan negotiations. This 3D view is superimposed by conventional 2D symbology like the Basic T. They provide exact values for speed, heading and altitude. To avoid the different elements of the display from concealing each other, some of them like the tape scales are made transparent and are placed on the edge of the display.

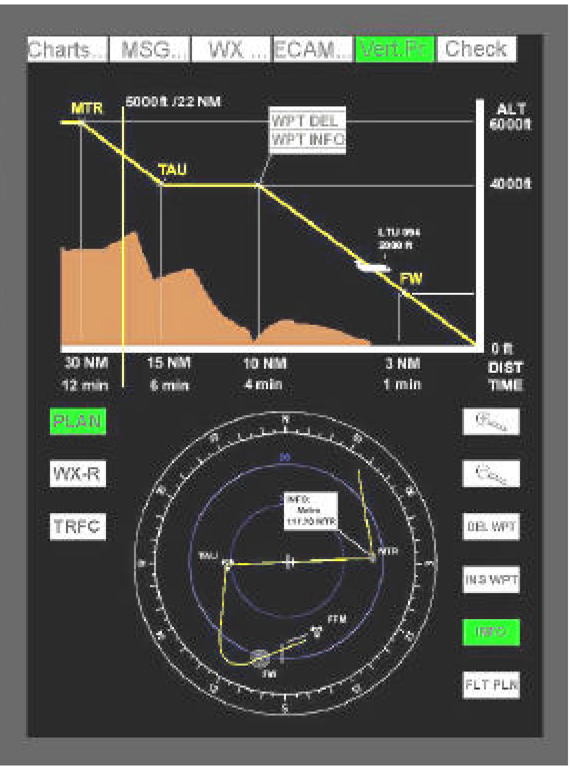


Figure 14 Primary Situation Display [Fol98] Figure 15 Multi Function Display [Fol98]

Cavok Primary Flight Display

In the design of the PFD, much attention has been paid to redundancy of information. For example, there is the altitude information given during the approach phase:

The first clue to the present altitude is given by the size in which the grid appears. In turn, it is displayed using perspective projection. This allows the pilot to estimate the altitude above ground at a first glance. During an ILS approach, the glide slope channel provides the required altitude very precisely in a purely graphical form. Shortly before touchdown the shadow of the flight path predictor moves into the field of view providing a very accurate altitude reference.

In addition to these graphical hints a digital readout is integrated in the altitude scale.

Another example of redundant information is the speed. The exact value can be obtained from the scale with its digital readout. As an intuitively perceivable presentation the movement of the 'outside world' - especially the grid - gives a sense of the actual speed. It is designated the visual flow field. Furthermore, the predictor changes its length and colour according to the actual speed of the aircraft, thus giving continuous feedback.

This redundancy of information helps to prevent the pilots from misinterpreting the presented data.

Cavok Navigation Display

The PFD has a limited field of view of 70° horizontally[Kau98[40]]. However, in order to enable the pilot to develop a complete image of the terrain, obstacles and adjacent air traffic, it was concluded, that the PFD should be complemented by a NAV Display.

The NAV Display format is computed from the same database as the PFD, containing the necessary information about the terrain underneath the aircraft. Though using a parallel projection, it also provides a three-dimensional impression (relief-picture).

The new display combines a conventional navigation display with a map and virtual elements such as navigational aids, air traffic routes, commanded or preplanned flight and taxi paths, and ground proximity warning symbology.

NAV display zooming is possible, allowing the pilot to observe an area of his choice in detail. In order to give the pilot an impression of the terrain and traffic surrounding him, the field of view may be selected with the pilots own aircraft at the centre or the lower edge of the display.

One example of the integrity of the PFD and NAV Display is the feature of the PFD viewing area, appearing in the NAV Display. This way the objects visible on the PFD can clearly be associated with the ones on the NAV Display.

Ground Movement

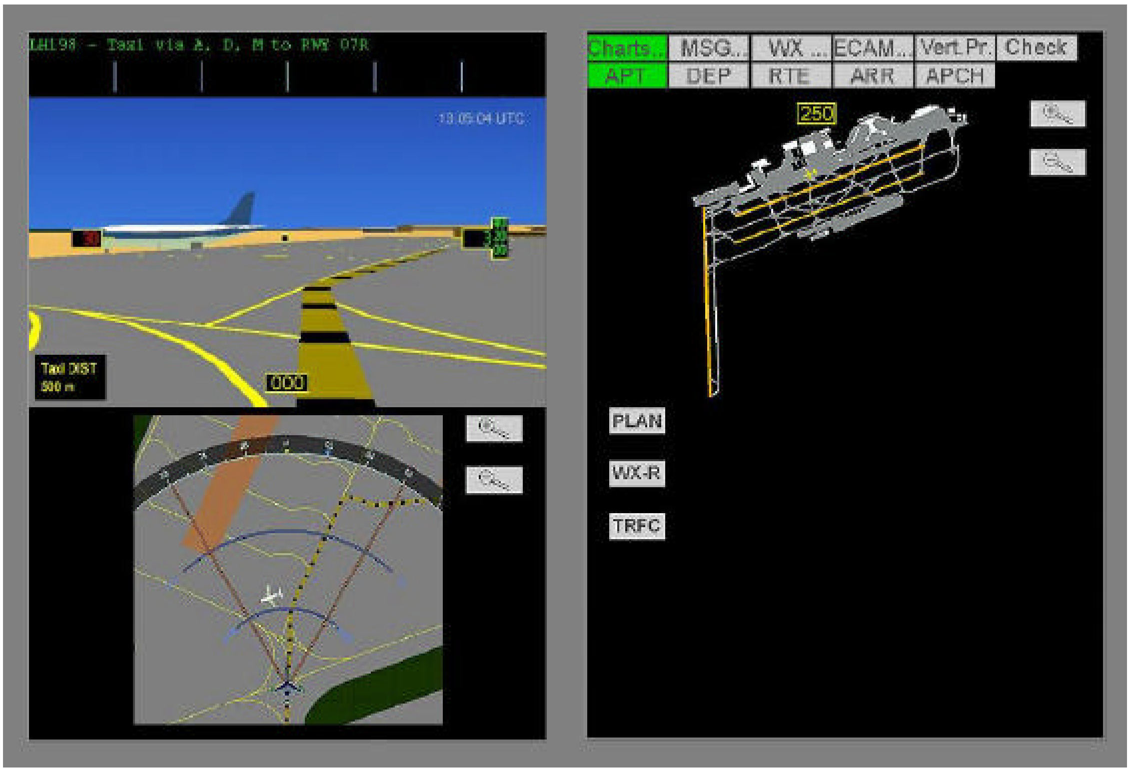


Figure 16 Taxi Symbology

A phase of flight that becomes more and more important for air traffic management is the taxiing at the airport[Lue98[35]] [Lie97[36]]. Both the Primary Flight Display and the Navigation Display support ground movement. The database contains a detailed representation of the airport; taxiways can be selected by the pilots or may be transmitted by ATC via data link. These selected taxiways are highlighted and also contain information about the required taxi speed.

In order to ease the steering task, a taxi predictor including a steering angle indicator for the front wheel is integrated into the NAV Display. In addition there is a predictor for the movement of the wingtips, which will be particularly helpful for steering future ultra high capacity aircraft.

Another design feature of these displays is the inclusion of dynamic or static obstacles. Though they can already be shown in simulation, a prerequisite for the final implementation is the ability to send digital data transmission between aircraft, ground vehicles and ATC, which is expected to be available in the near future.

	Visual Flight	Instrument Flight	Visual Flight (SVS)
A/C Attitude	natural	natural	natural
A/C Position	natural	coded	natural
Flight Path	coded	coded	natural
Terrain	natural		natural
Traffic	natural	coded	natural

Figure 17 Enhanced Situation Awareness

Enhanced Situation Awareness

It is hoped that new flight rules can be defined for IMC. While **I**nstrumental **F**light **R**ules (IFR) reduce flexibility and capacity tremendously, **E**xtended **F**light **R**ules (EFR) could break these limitations. With an integrated display system like the one described, synthetic visual flights are feasible (Figure 17). Today, visual separation in good weather condition is an important aid in reducing radar separation; in the near future it will be possible to do the same in IMC if the aircraft is equipped with technology like this. The 3D Display will greatly increase the pilot's awareness regarding their situation relative to terrain, obstacles and other aircraft. Since most information is presented in a graphical and natural way, it can be seized intuitively by the pilots. Especially in phases of high workload, the highly pre-processed information and its redundant presentation will contribute significantly to flight safety.

New possibilities like flight and taxi guidance integrated into a gate to gate concept will allow precise air traffic scheduling which in turn will save time, fuel and effort.

Flight Tests

In order to get feedback about the usefulness of a concept like the **C**avok **F**light **G**uidance **D**isplays (CFGD), extensive flight tests were conducted in 1996 with the co-operation of VDO-L. In August of 1997, a second round of flight tests was carried out at Frankfurt airport. Frankfurt was selected, because this airport has a high traffic density, a complex taxi environment and a good infrastructure.

The tested 3D Flight Guidance Displays were generated on a ruggedised Silicon Graphics workstation and visualised on an LCD. The test environment was the ATTAS test aircraft of DLR, a VFW 614. It seats 40 passengers and is equipped with a simplex fly by wire control (Figure 18).

Figure 18 ATTAS Test Aircraft

The Flight Guidance Displays were installed in front of the conventional instruments on the left side of the cockpit, while the safety pilot took the right seat (Figure 19). Pilots of Deutsche Lufthansa, Deutsche Flugsicherung, Aero Lloyd, Luftfahrt Bundesamt, DASA and test pilots from Airbus Industry flew the same task during three weeks.

The flight of about 90 minutes included taxi out, take off, climb, tunnel in the sky flights, low level flight under the ridge line of the Feldberg (880m), two ILS approaches at Hahn airport and then back to Frankfurt. Each pilot was introduced to the test aircraft systems and briefed concerning the new symbology, flight path and questionnaire. In the debriefing, pilots explained their impressions and filled out the questionnaire [Hel97a[37]].

According to the pilot's comments, the prevention of CFIT with this 3D Flight Guidance Display is excellent. The pilot is always aware of the environment he is flying in, and during the low level flights, dangerous terrain and escape routes are visible. So the goal of an intuitive and easy to perceive display was reached. Taxiing symbology helps the pilot to reach his gate in an advantageous way, while today the pilot has no onboard system support after touch down. The precision of the navigation and the database was very high. Comparing the external view of the taxi line and the synthetic one, pilots recognised a difference of less than half a meter [Hel98[38]][Pfi97[29]].

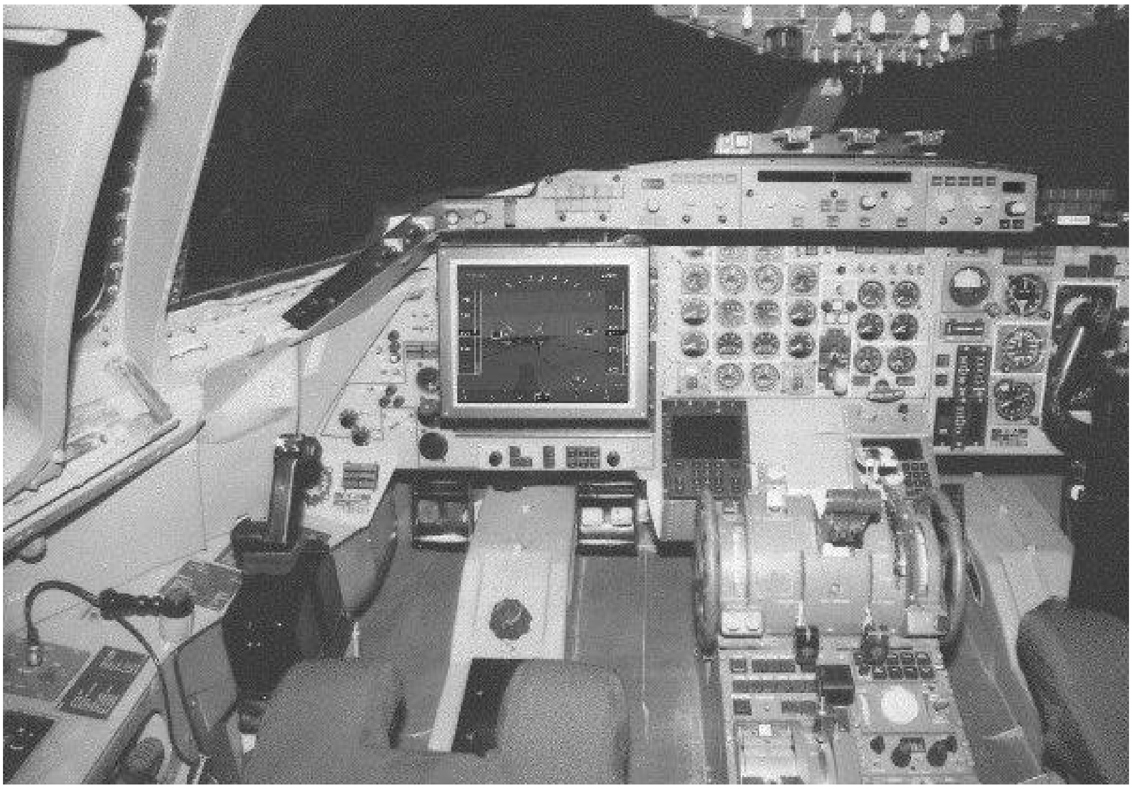


Figure 19 Experimental Cockpit

1.3.5 Motivation

The main objective of the synthetic vision system is to achieve a significant increase in pilot's spatial awareness. **T**actical **S**patial **A**wareness (TSA) shall prevent him from CFIT, today's main cause of accidents. TSA is supported by the PFD which shows terrain proximity in an intuitively perceivable way as demonstrated by several flight tests. The PFD also provides **S**trategic **S**patial **A**wareness (SSA) by showing the environment in front of the aircraft for approximately 100 seconds. Since this is a rather short period of time, SSA is primarily gained from the ND.

However, for strategic spatial awareness it is very important that the pilot remembers the environment for a certain period of time; even while he is busy with the execution of other cockpit tasks like FMS inputs or checklists. After this distraction, SSA as well as TSA have to be maintained or regained within a short period of time. Simulator tests at Darmstadt University have shown that TSA is quite intuitive and easy while SSA is very difficult and sometimes even impossible to maintain [Hel98a[39]].

From introspection, we proved that remembering a flight in a synthetic environment is very difficult compared to everyday experience. Compared to navigational experience in a well known environment, like flying to your hub under visual meteorological conditions (VMC), the problem of navigational experience in a synthetic environment is surprising. At a first glance there is no reason why it is so difficult to get familiar with an environment when presented as synthetically depicted terrain. Kaufhold [Kau98[40]] found that terrain recognition was rated good during the flight tests. This means that the outside view matches quite well with the synthetic presentation. So if the real and the synthetic environment are matching and Spatial Knowledge is quite easy to gain at familiar places, why is it then so difficult to get familiar with synthetically depicted environments?

Primary requirements are fulfilled as flight tests have shown. There is no kind of information such as navigational information that is missing in the Cavok flight guidance displays. The secondary or perceptive requirement is fulfilled, as the way of information presentation is excellent concerning perceptive aspects. Any proximate collision can easily be detected with the primary flight display.

However, beside ground proximity or impact detection which are skills on a very low cognitive level, spatial problem solving requires additional information. The abstract terrain presentation does not facilitate recognition. No recognition means no familiarisation with an environment after several approaches or fulfilled tasks. Being familiar with an environment allows the pilot to reduce the amount of attention paid to navigation and use it for other tasks. This indicates that the tertiary or cognitive requirement is not fulfilled.

Hypothesis:
The absence of a cognitive map during or after the use of the Cavok flight guidance displays is due to the poor adaptation of terrain presentation to cognitive requirements of the human. However, improvement of perception and cognition of synthetic spatial environment allows the creation of a cognitive map even in this environment.

1.4 Perception and Cognition in Large Scale Environments

In order to enhance the terrain presentation of the Cavok flight guidance displays the tertiary or cognitive requirements have to be analysed in detail. What are the cognitive requirements for the depiction of a synthetic environment? What is a cognitive map and on what is it based?

These aspects will be described form the psychological point of view and serve as a base for future developments.

During the last century, there were several approaches in psychology used to try to understand the human brain. In 1879 Wilhelm Wundt founded the first psychological laboratory and started scientific research on the human mind. The method he used and taught in his laboratory was introspection. Subjects had to reflect on their own thoughts and the experimenter collected and analysed this information. Totally contrary was the method of behaviourists like Gibson, who exclusively looked at external parameters like stimuli and reaction or behaviour of subjects without analysing the internal process. Between 1950 and 1970 cognitive psychology developed rapidly. Cognitive psychology tries to understand mental information processing. After a short introduction to sensation and perception, the idea of cognitive psychology will be applied to spatial problem solving.

1.4.1 Sensation and Perception

Stimuli are information about physical attributes of the environment that stimulate an individual. They are the connection between environment and individual.

Sensation is the process by which our sensory system gathers this information about the environment. The five senses of the human -sight, hearing, touch, smell and taste- are present in most animals with greatly varying degrees of functionality. The primary senses involved in navigation, sight, hearing, and smell, are also the senses capable of distal perception. That is, they can perceive stimuli at locations remote from the body. These are the senses that enable individuals to explore an environment larger than the space that can be reached locally for touching and tasting.

Figure 20 illustrates the process from stimulation to perception. Stimuli reach the brain through a complicated process involving electrical pulses, nerves and chemicals. A painful stimulus (for example, a burn or cut) begins the process by stimulating a free nerve ending located in the skin. Chemicals are released which sensitise these pain receptors. The receptor turns the stimulus into an electrical pulse beginning at the primary neurone. The impulse moves along the secondary neurone (afferent nerve) through the spinal cord and continues through a tertiary neurone in the brain to the cerebral cortex, where the general sensory centre is located. Here the impulse is decoded, that is, the sensation of pain is felt or perceived.

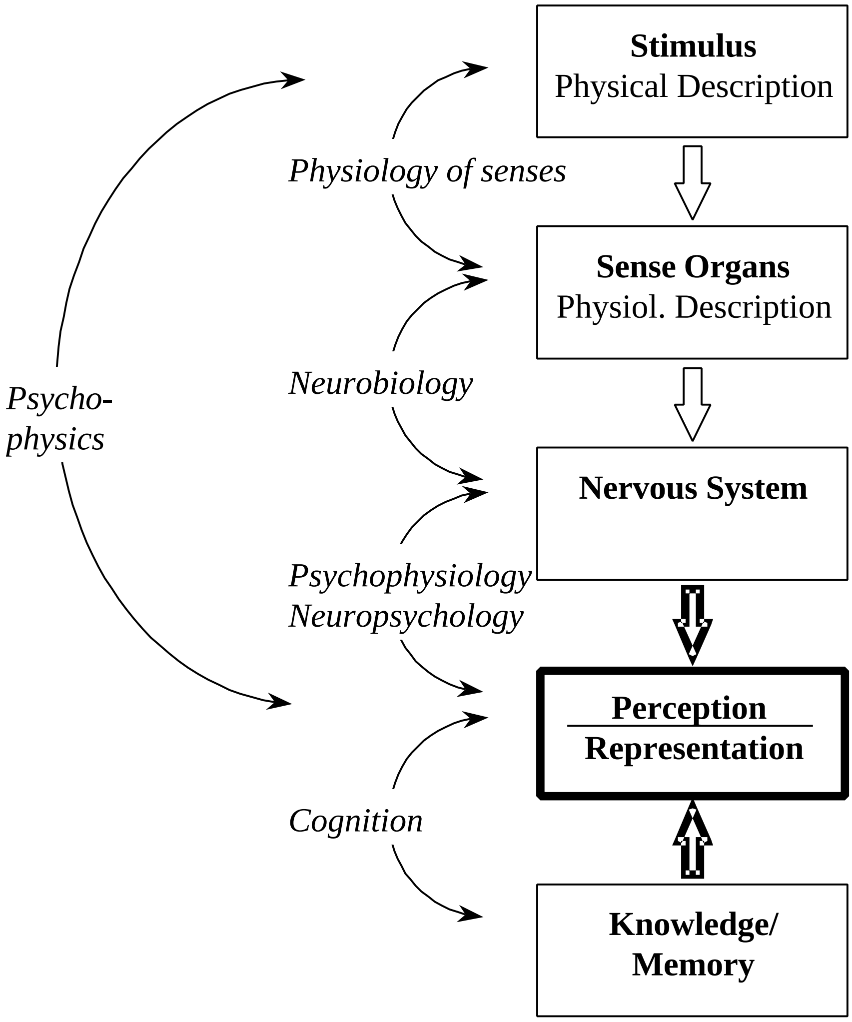


Figure 20 Overview of Research Areas on Perception and Cognition [Gib79[41]]

Perception is the selection, organisation and interpretation of sensations. Since the amount of stimuli reaching an individual at the same time is very high, some sensations are filtered and others are selected. A good example is a discussion during a party in a crowded room. While we are paying attention to one special person, his voice can be selected from all the others. Besides emphasising a certain stimuli, the selection of contrary information has to be managed. So existence of stimuli or even sensation does not always result in perception.

1.4.2 Spatial Cognition in Large Scale Environments

Cognitive psychology is part of the general psychology concentrating on mental information processing or cognition. Cognition is the mental activity by which an individual is aware of and knows about his or her environment, including such processes as perceiving, remembering, reasoning, judging, and problem solving.

The analysis of processes from stimulation to perception as it was mentioned in chapter 1.4.1 is based on the Sternberg paradigm. Sternberg distinguished the task of detecting a certain number from several one digit numbers into several operations. He evaluated this model by measuring elapsed times for different operations. This method of defining operations in information processing is implicitly included in the distinctions among perceiving, remembering, reasoning, judging, and problem solving.

Further explanation of spatial cognition will be based on the Sternberg paradigm since it has been quite advantageous in the past. For describing complex cognitive processes, steps of discrete and abstract operations will be analysed.

The ability to recognise spaces, i.e. to imagine what a larger-than-perceivable world would look like, requires spatial cognition. Spatial cognition overcomes the lack of direct sensory information (perception) about the whatness, whereness, and whenness of places in our environment by taking advantage of past experience (representation). We recall information from memory and manipulate it to solve the spatial problem. The key to the manipulation is the plan. The plan is simply a guide for spatial behaviour, a perception for a sequence of actions that will result in solving the spatial problem. It is the outcome of a series of interrelated cognitive operations [Dow77].

While the environment includes everything that is not the individual himself, the expression will be used as spatial environment meaning topological or geographical surface. In literature, environment is distinguished into small and large scale environment. One definition is given by Kuhn: Small scale environment includes objects which are smaller than human, movable and whose exploration is realised by manipulation. In a large scale environment objects are bigger than humans, the explorer is in motion and exploration is realised by navigation [Kuh98[42]].

Another definition for large scale environment by Kuipers [Kui78[43]] is:

A space whose structure cannot be observed from a single viewpoint. Naturally, this definition depends on the observers, so a city might not be large-scale when viewed from an aircraft, while a map might be large-scale when viewed through a small hole.

This definition applies to large worlds such as continents and oceans, small worlds such as molecules viewed at a large scale, and small worlds such as building interiors which cannot be viewed in total due to occluding walls [Kuh98].

Many typical activities in which people take part every day involve the performance of spatially cognitive tasks in large-scale environments. These tasks are based on spatial knowledge which is gathered from the environment itself. Spatial knowledge includes perceptual information (e.g. What does a place look like? What does it sound like?) as well as information about distances and directions in general interrelations of places. It also includes inferred knowledge about distances and directions from place to place. Moreover, it includes inferred knowledge about places unseen and paths untravelled [Dar97[44]]. Thorndyke describes spatial knowledge in terms of three levels of information:

1. ***Landmark knowledge*** represents information about the visual details of specific locations in the environment.
2. ***Procedural knowledge*** (also called route knowledge) represents information about the sequence of actions required to follow a particular route.
3. ***Survey knowledge*** represents configurational or topological information.

These types of spatial knowledge are *not* mutually exclusive. Each level of knowledge builds on previous levels of knowledge. Landmark knowledge is strictly static information [Tho82[45]].

This three level description of spatial knowledge will be referred to extensively in the next section involving the cognitive map theory.

1.4.2.1 Cognitive Map Theory

For many years, psychologists have been interested in the ways in which people mentally manage space. The term "cognitive map" has been used to describe the process of formulating and maintaining spatial knowledge. Research in this area has focused on knowledge representation and organisation, knowledge acquisition, and knowledge accessibility on demand. This section will survey the literature on cognitive map theory. The goal is to understand the cognitive processes and resources associated with wayfinding in order to develop a scientific foundation for the design principles to follow.(Darken)[Dar97].

Tolman conducted a number of experiments with rats to determine if their behaviour supported the stimulus-response model held by the behaviourists or if a more complex mental phenomenon existed. Tolman showed that rats did in fact learn spatial locations from their environment, dispelling the view that their actions were simple stimulus-response connections. To illustrate this he conducted one experiment where rats were trained to find the food box (G) (See Figure 21).

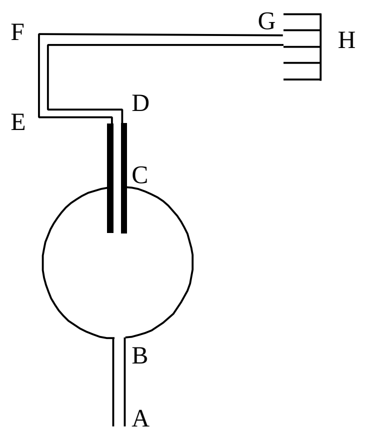


Figure 21 Tolman's Training Maze

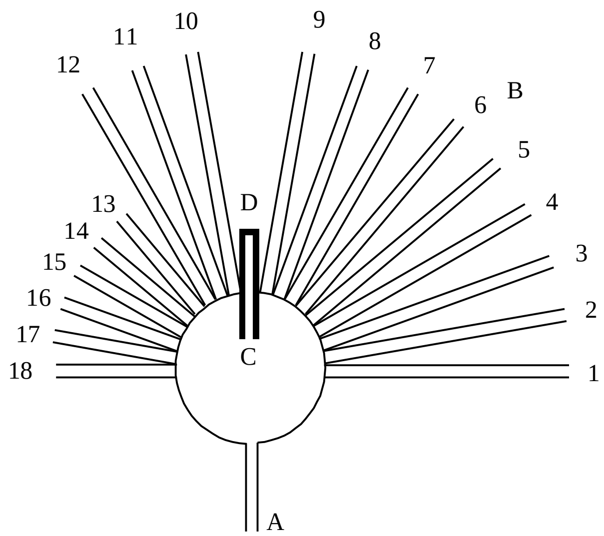


Figure 22 Tolman's „Sunburst" Maze

After a training period, the rats were moved to the “sunburst” maze. If their behaviour was a simple stimulus-response connection, the rats would investigate the blocked path. The data clearly showed that the rats headed directly to the food (path 6) showing that they had inferred the direction from the previous trials. Although this early work showed that learning had taken place, it did little to explain what knowledge had been acquired or how it was represented.[Tol48[46]]

These questions will be discussed in the next chapters beginning with a short excursion into neuroscience. Then, the cognitive map theory will be discussed in detail starting with ontogenetic development and concluding with spatial problem solving. Further on, questions about rotation, translation and fusion of different cognitive maps will be adressed.

1.4.2.2 Cognitive Mapping and the Function of the Brain

There are two different but related approaches to understanding the function of the brain: the more familiar neurophysiology and neuropsychology. Operating at the microscale of brain morphology, neurophysiology deals with the biomechanical and bioelectrical functioning of the 100 billion neurons that make up the essential physical matter of our brain.

Many neuropsychologists adopt a macrolevel viewpoint, seeking links between the gross morphology of the brain and the normal range of mental and behavioural abilities [Dow77].

Researchers in a variety of scientific disciplines are working together to understand how the brain interprets internal and external information; how it controls movement, creates thoughts, and learns; how it produces our intelligence and our humanity; and how it generates devastating illnesses. Nearly 2,500 years after Greek physicians first declared that human mental life emerges from the brain, the interdisciplinary focus on how the brain works and how it is affected by disease has benefited immensely from recent revolutionary advances in molecular biology, biomedical imaging, structural chemistry, immunology, psychology, and computer science. By most calculations, 90 percent of what we know about the brain today derives from research over the last ten years.

Why did this progress come so slowly? Nineteenth century neuroscientists had determined that the twin lobes of the cerebral cortex were the seat of higher cognitive functions, but they were stymied by the complexity of more than 100 billion interconnected neurons and other brain cells. In addition they were hindered by the brain's inaccessibility: its protective case shields it from the prying eyes of researchers as well as injury and disease.

Those obstacles began to disappear about forty years ago with the advent of both modern molecular biology and computer technology. Together, these two disciplines provide most of the research tools that enable investigators to see the workings of the brain at all levels, from the molecular to the behavioural. With recombinant DNA technology and its many spin-offs, neuroscientists can analyse the relationships that produce nerve signals. Using computerised monitors, investigators are beginning to decipher the electrical signals that produce a given thought or behaviour. Computer-controlled imaging technologies --first, **P**ositron **E**mission **T**omography (PET) and now **F**unctional **M**agnetic **R**esonance **I**maging (fMRI)-- provide a window into the brain.

From such research we have learned that the brain is structurally and functionally modular. Just as each of the heart's four chambers has a unique role in pumping blood, discrete regions of the brain perform specific tasks of a particular mental function [Coh97[47]].

For the first time, advanced imaging techniques have revealed the moment-by-moment brain activity involved in seeing a face or a series of letters, holding it briefly in working memory, and then recalling it. Two research teams supported by the **N**ational **I**nstitute of **M**ental **H**ealth (NIMH) report on the studies using fMRI. The new studies are the first in humans to demonstrate sustained activity in the prefrontal cortex while information is held in mind. Contrary to prevailing theory, one of the studies shows that brain circuits for seeing and remembering are not separate. Rather, they span processing centres arranged along a "continuum," each with its own mix of somewhat overlapping functions, from "mostly perceptual" areas in the back of the brain, to "mostly memory related" regions in the front.

A research team at NIMH, scanned subjects during a task in which subjects had to keep increasingly longer series of letters in their minds. Brain areas involved in memory distinguished themselves by working harder as the load of letters got heavier.

Brain circuits that process short-term information differ from those that store long-term memory, much as a computer's **R**andom **A**ccess **M**emory (RAM) differs from hard disk memory. Working memory is used for such tasks as holding a phone number in mind just long enough to write it down, as well as in higher cognitive "executive" functions -- planning, organising, rehearsing.

The new studies are the first to examine the time-course of working memory using fMRI. The fMRI tracks telltale signals emitted by oxygenated blood in a magnetic field to reveal what parts of the brain are active at any given moment. Whereas earlier brain imaging studies using radioactive tracers could only see averaged activity sustained over minutes, fMRI captures events that last just seconds.

This higher speed resolution reveals both the location and the timing of brain events, permitting researchers to pinpoint and quantify the amount of activity related to perception and memory tasks for each brain area involved.

The NIMH researchers scanned the brains of 8 individuals while they performed a visual task. Subjects viewed a face on a computer monitor for 3 seconds, held the face in memory (with no visual stimuli) for an 8-second pause, and then viewed a second face for 3 seconds. They pressed a button to indicate whether or not the faces matched. Subjects were also shown scrambled faces under the same conditions, to control for mere visual stimulation.

Areas at the back of the brain were only briefly activated (when the face was shown), confirming their primary role in perceptual processing, while front areas stayed active during the pause, signalling a predominant role in working memory. Yet, some rear areas activated slightly during the pause, while some front areas responded modestly just to visual stimuli. Strikingly, through six key areas along the continuum from back to front, response to visual stimulation dropped steadily, while response during the pause increased steadily [Coh97].

The basic differences in brain function should not be confused with the relationship between the right-brain and the left side of the body, and that between the left-brain and the right side of the body. Thus the right-brain controls the motor functions, including vision, of the left side of the body; these are known as the contralateral functions. The functions of interest here are best illustrated in [Bog72[48]].The left hemisphere is the locus for verbal language (which is largely responsible for its designation as the major hemisphere), difficult calculations, and the process of sequential, logical reasoning using verbal ideas. In contrast, the right, or minor, hemisphere is the locus for the appreciation of the arts, for emotions, and, of greatest importance, the spatial abilities. Included in this latter category are abilities to perceive spatial relations, to remember places and locations, to use spatial imagery, to wayfind, and to engage in geometrical thinking [Dow77]. However, neuro-science may have advanced in the last decades pinpointing cerebral areas responsible for discrete tasks, this microscale point of view is still very far away from applications in cognitive science.

1.4.2.3 Development of Cognitive Mapping Ability

The term development can be, and has been, applied to both ontogeny and phylogeny.

One view of development suggests that the unfolding sequence of ontogeny (individual development) recapitulates or mirrors the sequence of phylogeny (evolutionary development). While this view should be regarded critically, it is certain that higher mobile organisms develop the capacity for cognitive mapping, that such development is not restricted to human beings, and that such development is a necessary prerequisite for survival in the face of the continual spatial problem-solving demands posed by life on a large-scale, two-dimensional surface.

According to developmental psychologist Jean Piaget [Pia67[49]], children go through four distinct stages of formal operations of cognitive development. These stages are best described by the frame of reference the child uses to locate and orient objects within the environment.

The *sensorimotor* stage (birth–2 years) is characterised by the child's ability to experience the world only through the senses. A child in this stage is limited in both his motor and cognitive capabilities making wayfinding and object orientation a non-issue.

In the *preoperational* stage (2–6 years), the child is only able to locate objects in the environment relative to the body. These children are characterised by their *egocentric* frame of reference in which objects are recognised only from familiar perspectives. A house recognised from the front will not be recognised when viewed from the side or the back.

Operational Development	**Frame of Reference**	**Spatial Relations**
Sensorimotor	n/a	n/a
Preoperational	Egocentric	Proximity Separation Open/Close Between Order
Concrete Operational	Fixed	Enclosure Continuity Geometry
Formal Operations	Coordinate	Proportional Scale Reduction Distance Estimates Coordinates

Table 1 The Development Stages of Formal Operations and Spatial Ability

A child in the *concrete operational* stage (7–9 years) develops a *fixed* coordinate system in which the body and other objects are oriented relative to static landmarks in the environment. A fixed coordinate system enables recognition from multiple perspectives but only within the constraints of the known coordinate system.

Finally, in the *formal operations* stage (11 years), the child is able to orient himself to more abstract coordinate systems external to the body. Formally operational children orient in a *coordinate* frame of reference. In this case, abstract frames of reference are used such as the cardinal directions, polar coordinates, and latitude/longitude.

Within these frames of reference emerges the ability to form spatial relations. Topological relations are the first to appear. Properties such as proximity, separation, open, close, between, order, enclosure, and continuity develop during the preoperational and early concrete operational stages. This is followed by projective relations such as straight lines and triangles which are invariant with changes in perspective. The last type of spatial relations to develop are Euclidean relations such as proportional scale, reduction, distance estimates, and coordinates. These abilities are often categorised in terms of two spatial factors; visualisation and orientation [Gee79[50]]. Visualisation involves the ability to mentally manipulate a visual stimulus whereas orientation involves the comprehension of the arrangement of elements within a visual stimulus. Both factors directly relate to higher level spatial tasks such as spatial problem solving [Tho83[51]].

Geographical educators have stated that children should not be fully capable of learning to interpret aerial photographs before the age of ten at the earliest. Two findings are remarkable in the face of this assertion. First, children display this interpretation ability nearly full-blown before school-entering age. Development of this ability appears to be complete before the age of nine. Indeed, the skills attained go beyond simple recognition and interpretation. First-grade children can identify houses and roads, trace them, name the shapes drawn on the tracing (after the photo has been removed), colour code the shapes, and finally, draw a pencil route over roads connecting two widely separated houses. All of these performances depend upon cognitive mapping for recognition, interpretation, manipulation, and spatial problem solving.

The second remarkable finding is that the photo-interpretation ability seems to be independent from a specific location, culture, or educational system. One study of aerial photo interpretation involved kindergarten children in four Puerto Rican communities. One hundred and eleven out of hundred and fourteen children succeeded in identifying two or more features in each of the photographs of the four communities. The children did not perform significantly better with photographs of their own community than with photographs of the other three communities. Urban children did not perform poorly on rural images and vice versa.

These abilities are fully developed from an age of about eleven and give humans the ability of spatial problem solving.

1.4.2.4 The Process of Cognitive Mapping

Acquisition of Cognitive Maps
The perception of environment and integration into a cognitive map significantly depends on the interaction of the human and the environment. The interaction can be classified into navigational and configurational. Navigational and configurational knowledge differ in the point of view people have on the experienced layouts. Point of view expresses the natural visual perception using a “horizontal“ view or viewer centred look, according to the situation in which one has encountered the town or large scale environment. The point of view in configurational knowledge is described as a bird’s eye view, namely like the view a person has when encountering a map or a model of the layout -a view from above [Sch97[52]]. While navigational perception requires mental mapping of objects presently visible, the configurational allows to get a fast overview of the environment.

Navigational

The interaction of sensory perception and motor experience seems to be essential for normal environmental learning. This may be described by the distinction between active and passive spatial experience.

Several experiments have been done for evaluating different perceptions during slide or video presentations or during an active walk in real environment. Gale et al. [Gal90[53]] observed in a navigation task that training using video tape had to be repeated five times until the learning effect was comparable to a single walk [Gil97[54]].

Active spatial experience involves walking cycling and driving; passive experience involves riding or being driven around. When approaching an intersection there is an important difference between having to decide what direction to take and feeling or monitoring the result of that decision and having both the decision and action taken for you. Thus, to learn how to learn spatial environments, one must experience a variety of environments and experience them actively.

Passive spatial experience of a new environment can result in confusion and uncertainty, one never seems to get the layout of an environment “straight“ in one’s mind.

Configurational

Configurational or cartographic perception can reduce faults in the orientation of the mental map or the subjective impressions of perceived distances. Additionally, features that may be invisible from certain points of view can be mapped and easily integrated into the cognitive map. Thorndyke and Hayes-Roth [Tho82] could show that subjects who perceived their spatial knowledge from a map had a better performance in estimating Euclidean distances of landmarks than subjects who perceived their spatial knowledge by active navigation. Thus, if available, external maps should be used for supplementary internal mapping.

Sources of Information

Sources of information as an external requirement for perception and cognition include significant places and objects. While in general a lot of common objects like trees, mountains or rivers are filtered out, easy recognisable they may be important sources of information if they are unique or easy to be recognised. Sources of information have to be looked at under the aspect of usability. Which behaviour can be supported, which kind of representation will result? It is not important to list all kinds of sources. In the following chapters, some typical ones will be analysed [Gil97].

Local and Global Landmarks

Landmarks are distinct, significant locations or objects in the spatial environment. Merkel [Mer80[55]] mentions landmarks as tools. The amount of information of local and global landmarks may vary. Global landmarks are visible from larger distances and may serve as a kind of compass. Poucet [Pou93[56]] emphasises that spatial relations of local landmarks can be mapped by active motion between them. Spatial relations between global landmarks, however, are easily mapped only if they are visible at the same time, or if the observer is able to see both only using head movements. While local landmarks especially support local decisions of motion, global landmarks are used to recognise direction and frames of reference.

Children up to 6 years old are only able to use local landmarks. From 12 years onward, they have the ability to use both local and global landmarks. Characteristics which determine whether an object is selected as a landmark are of physical nature (colour, size), but even the position relative to other objects or landmarks determines the selection. What kind of visual characteristics are necessary to be selected as a landmark? Objects close to decision points (intersections) are mapped more often than others, but even characteristics like individual preferences that may not support the process of problem solving are important.

Creating Cognitive Maps

The distinction between response and place learning lies in the nature of the learning process, the way in which spatial information is integrated, and what finally emerges as the way of coping with spatial problems.

Landmark knowledge represents information about the visual details of specific locations in the environment. It is memory for salient perceptual features in the environment such as an architecturally unique building that dominates the skyline. Kuipers refers to this information as *perceptual icons* or *images*. This type of information is obtained by directly viewing objects in an environment or by viewing indirect representations such as photographs. Location recognition is accomplished through landmark knowledge. Presumably, an image of the current scene is matched against known or previously viewed scenes (Figure 23).

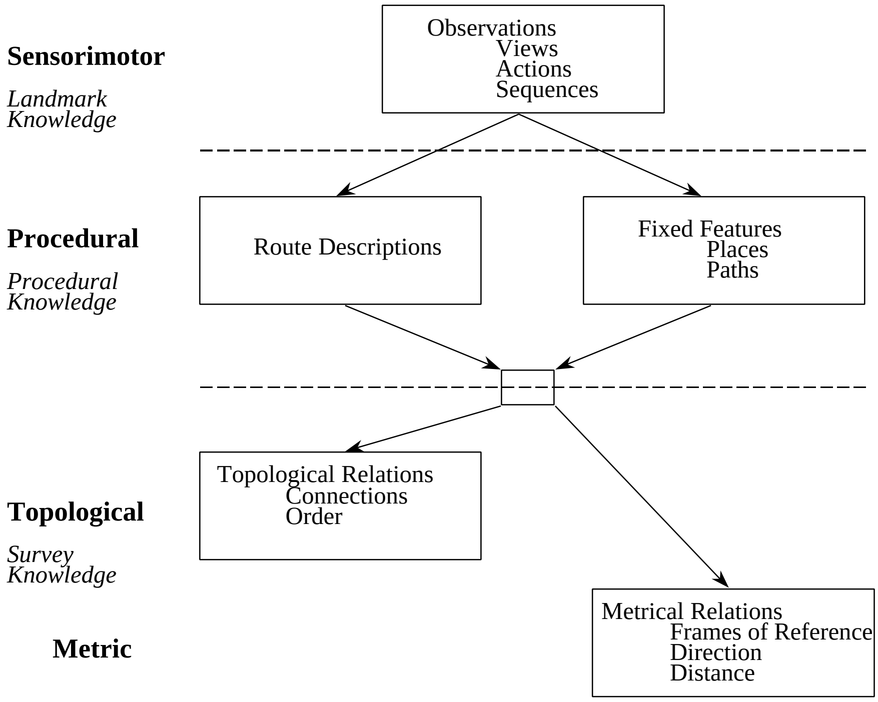


Figure 23 Kuiper's Cognitive Map Model [Kui78]

Route Mapping

Procedural knowledge (also called route knowledge) represents information about the sequence of actions required to follow a particular route. This has four components:

- A sequence of actions which constitutes a route description
- A series of perceptual features encountered along the route
- Distances between locations experienced as sensations of motion, speed, and time
- Angles or bearing changes at turning points along the route

In other words, procedural knowledge connects isolated bits of landmark knowledge into a larger, more complex structure. This type of knowledge is obtained either through direct experience or through simulated experience such as video [Tho82]. Both landmark and procedural knowledge are defined in terms of an egocentric frame of reference.

Survey Mapping

Survey knowledge represents configurational or topological information. Object locations and inter-object distances are encoded in terms of a geocentric, fixed frame of reference. Survey knowledge is map-like in nature. Accordingly, it can be obtained directly from map use. However, there are complications with this method dealing with inflexibility of the corresponding representation. Extended exposure to direct navigation of an environment also leads to survey knowledge.

Summary

Place learners engage in survey mapping, which produces an array of places with a rich “mesh“ of associated connections among them. These survey maps begin as a collection of simple route maps; that is a set of specific behavioural responses to specific problems and plans. People who typically follow only a few well-established paths in their routine never get beyond this stage. On the other hand, people who make more varied trips cease to view their trips as following individual and quite separate routes. They recognise a spatial relationship among the routes which transcends the sequential elements of a specific trip. The comfortable feeling they achieve comes from a qualitatively different form of knowledge of the environment than that of the response learners. The response-learned pieces have been fitted into a new and more coherent whole. This new, dimensional whole permits a more flexible and superior approach to spatial problem solving. Thus, if a route to some goal is blocked, the place learner knows how to detour onto other routes in order to get to his destination. Place learning does not supersede response learning in all environmental contexts; rather, most people are capable of doing both. People who use survey mapping can shift to route mapping when the occasion demands. Such downshifting often occurs when one first arrives in an area or when one is confronted with a physical environment that literally defies successful survey mapping. In the sense that one kind of learning typically precedes the other, this downshifting from the more advanced to the more primitive seems the reversal of development. Other psychological evidence suggests that a learner shifts from cognitive mapping to stimulus-response learning in situations of stress, of disturbance, or in the face of other difficulties and impediments. The graduation from response to place learning is influenced by four major factors: the form of the physical environment, the type of spatial experience, the duration of that experience, and the age of the person involved. It is difficult to say that any one of these factors is more important than the others; however, it is possible to say that the nature of the physical always constraints the process (as well as the product) of environmental learning, and these constraints apply equally to response and place learning [Dow77].

References in Cognitive Maps

Location

The specification of location requires something more than an identifying name; what is needed is a location description. This can take one of two forms: state and process. A state description of location tells where something is located in terms of a well-known and commonly understood system of coordinates. A process description is a set of instructions telling how to get to a particular location. A simple micro-spatial example of the distinction between state and process descriptions is provided by an analogy drawn from the chess game. The location of any chess piece can be described either in terms of the designation of the chessboard square on which it is located (state) or by the sequence of moves through which it got there (process). In geographical macrospace, the same state-process distinction holds true. One form of the state description is a set of cartographic map coordinates (e.g. latitude and longitude in degrees, minutes, and seconds). A second form is an intersection of routes or airways. The first form of state description refers to a universally agreed-upon set of coordinates that are imposed on the earth’s surface and that have a well known point of origin. The second refers to a street pattern or spatial pattern familiar to the pilot. In certain situations, maps based on coordinate systems are used without any identifying place names.

These are two fundamental forms of location description. Both are used in cognitive mapping, depending on how the environment is organised, the quality of the existing cognitive map (process first and state later), and the individual age (process first and state later). Both state and process descriptions depend on frameworks of understanding which people impose upon the world. The frameworks are not absolute property of the world. The coordinate systems, whether compass based or pattern based, are designed by people for their own use. This means that the use or application of a cognitive map has significant influence on the cognitive representation of locations. State and process descriptions of location are neither always equally useful nor always interchangeable. In general, where the layout of available paths is sufficiently regular so that both types of description can be used, state descriptions offer greater flexibility in two important ways. First, a knowledge of origin and destination and of the overall layout of an area usually permits a choice among a number of alternative paths, while a process description refers to one specific path connecting origin and destination. Second, it is more parsimonious and simple to learn the “rule system“ that governs the pattern of a complex airport (which is necessary for the state description) than to try to reach many different places on the apron by memorising a large number of specific paths or process descriptions.

One way to avoid the choice between state and process descriptions to a location is via redundancy, the use of both.

Distance

Distance is a measure of the amount of spatial separation between two locations. Such simplicity is misleading. The problem of how separation is expressed (e.g., what units are used) is complex. On the one hand there are „absolute“ or objective measures of distance, including familiar units such as nautical miles, kilometres and metres. These measures are based on arbitrary but commonly agreed upon fixed units. On the other hand there are „relative“ measures of separation which depend on the ability to overcome the effects of separation. Relative or cost measures of distance are in large part a function of the tool available for overcoming distance. Some means of travel, such as aircraft, reduce large distances to short periods of time. Regarding cognitive distance there are two aspects. The first is the units of measurement used to cope with the problem of thinking about and expressing distance. Even if units are standardised in aviation the mental representation should be considered. Second, factors that affect people’s estimations will be discussed. This requires research on the accuracy of distance estimations compared to “real world“ distance measurements.

Direction

The last basic component of cognitive maps is direction. The term direction, directions, and orientation are discussed together here, because they frequently appear together and they are easily confused. A considerable difference exists, for example, between direction and giving directions. Directions given to an individual are, in general, simply process descriptions of location - a statement of how to get somewhere. A direction, however, can only be specified only with reference to a coordinate system. Thus, the direction of a vector in mathematics or physics is the angle that it builds with the horizontal or x-axis in an xy plane. Direction on the two-dimensional surface of the earth is specified in degrees of path deviation from a northward-pointing compass needle. Even if these precise vectors are common in aviation and the pilots are used to them, they are not very helpful in an imprecise and generally irregular world.

Orientation means knowing, or understanding, location and the spatial relations between locations. In this common usage, orientation is rooted in state descriptions; hence, in a coordinate system. Someone is oriented when he knows where he is now (present location), and he can link this location with a series of other locations. The link with other places can be expressed using either process or state descriptions. Most importantly, orientation is basically a cognitive act, since these other places can lie well beyond the perceptual range of any of our senses. Orientation refers to the link between knowledge of the spatial environment and the environment itself, between cognitive map and real world.

1.4.2.5 Types of Cognitive Maps

Application

One can treat the spatial environment in two ways: as consisting of innumerable particular (unique) places or as consisting of a limited number of general types of places and objects. These choices are not mutually exclusive nor are they imposed on one by the nature of one’s environment. Cognitive maps are a blend of knowledge of the particular and general.

Our problem-solving ability can take advantage of the repetition of both the specific problems (e.g. approach to a difficult airport) and classes of problems (ILS approaches).

It is always possible to generate a route map by selecting cues and linking them to a sequence of behavioural actions, but for an area to be place mapped, it must provide the opportunity for a variety of travel experiences within it to test these rules. Some of the possible ways of place mapping an area will take precedence over others. One tries to learn a set of rules that can cover as wide ranges of spatial problems as possible. This search for generality and flexibility leads to the development of a heuristic - a general set of rules for coping with route choice, directional change, direction giving, and so on. Heuristics are rules of thumb which generally work; for example, one tends to look for elevators in the corners of buildings. All that you have to do is tailor the general rules to fit the specific identity of a particular city. Once created, heuristics can be transferred from one environment to another sharing some common structural characteristics.

The general is treated as an equivalent category. Attention is paid to the limited set of shared characteristics that have been generalised from repeated experience with different instances of a type of place or object. One emphasises characteristics that allow one to typify, that allow one to group together places, and that allow one to say that this is an example of a taxiway intersection or a typical approach profile.

The particular is remembered through an identity category that consolidates the salient features of the direct and indirect experience of a place.

1.4.2.6 Spatial Problem Solving

Since it is impossible to avoid spatial problems in our everyday lives, they have to be solved. Survival and happiness depend on finding successful solutions; you have to develop ways of problem solving that are highly reliable and accurate. On the other hand, since human beings face countless spatial problems on a daily basis and yet never have enough time to do everything that they want to do, problem solving must not only be reliable and accurate, but also as fast and flexible as possible. If on your way home you come to a blocked street, you must make a quick decision about which alternative route to take.

One might think that when following a wellknown path, cognitive problem solving is not necessary. The habitual problem solution is best exemplified by the familiar belief that you know something like the back of your hand and can make certain journeys blindfolded. You can walk home thinking about something else without being aware of how you solved the spatial problem of getting from one place to another and without any memory of that particular journey. However, the lack of a conscious memory does not mean that your cognitive mapping ability was dormant. You were looking ahead to anticipate where to cross the road, where to turn and where to stop. A sequential plan was being executed and your spatial progress monitored. Had you been disturbed in your thoughts by some person or event, you would have known immediately where you were in relation to home or work. You were well oriented. Such a habitual problem solution is simply the result of learning, of the cumulative experiences of many similar journeys in the past. This learning and these past experiences have been organised by the same cognitive ability that is controlling your spatial behaviour on the way home.

Wayfinding describes the process of solving one class of spatial problems, the movement of a person from one location on the earth’s surface to another. For convenience of discussion, the process can be distinguished into four sequential and interrelated steps:

- Location and Orientation
- Planning
- Control of track
- Discovery of objective

Location and Orientation

Location and orientation as the first step in wayfinding is key. You have to recognise your own position (locate) and a direction (orient). There are two ways of finding a location: first you can locate your position absolutely in an external map; second, you can locate your position relative to a number of landmarks. Absolute location usually requires some navigation tools, so human beings usually locate relative to landmarks. The link between a cognitive map and perceived environment comes from selected places that act as landmarks. The present location can be fixed by mentally figuring out the position relative to these landmarks. Orientation can also be distinguished into two processes: first, the absolute orientation using cardinal directions like north, east, south and west and second, the relative orientation from the present position to a landmark. Haugen [Hau57[57]] distinguishes between two systems of orientation. The first, proximate orientation, refers to celestial observations of directional relations between places in one's immediate neighbourhood. The second is ultimate orientation.

Planning

The choice of route requires that a person makes a cognitive connection between his current location and that of the desired destination. To be useful, this connection must be converted into a plan of action, usually by a sequence of directed movements which hinge upon a series of landmarks. Each landmark represents a decision point: Turn left at the corner, take the third right, and look out for the grey and orange house. A plan is a complex hierarchy of actions that will get a person from point A to point B.

Control of Track

The third step in the process, staying on the right track, monitors the execution of the route plan. This part of wayfinding was largely responsible for the idea that wayfinding was an innate process. However, staying on the right track is achieved by keeping our cognitive map tied to the perceived environment and by taking appropriate actions at each decision point. The plan itself is reinforced by repeated performances of the same journey and eventually becomes a sequential route map. Two locations are mentally linked by a path that is punctuated by a sequence of landmarks. The landmarks are the means of linking cognitive map and the perceived environment. They allow travellers to monitor spatial progress and to stay on the right track.

Discovery of Objective

Assuming that one has mastered the environmental maze, one faces the final step, the discovery of the objective. You need to recognise when you get to where you are going. Again, this recognition depends upon linking a cognitive map with the perceived environment.

1.4.2.7 Fusion of different Cognitive Maps

Humans can gradually integrate several sequential route maps. The integration follows from shared end points and landmarks, and you develop a spatial route map. These wayfinding experiences are woven together. They are no longer separate and unrelated bits and pieces. The result of the mental weaving process is something approximating to a traditional cartographic map, something that can be added to and amended as both needs and the spatial environment change. These cognitive representations of spatial relationship overcome the unsystematic way in which we get to know the world around us.

In my opinion, this process is a learning process that results in a more detailed cognitive map. The temporary fusion of different maps should be possible. General maps that are applicable to several airports or environments can be integrated into a specific or particular map and replace information that is not available. But this integration will not result in a more detailed map since general information stays general and will not be mapped twice.

1.4.2.8 Problems in Cognitive Mapping

After identifying the process of cognitive mapping, one should focus on the outcome of the process, especially accuracy, similarity and errors in cognitive mapping. Accuracy involves comparing maps with the “real environment“ while similarity involves comparing maps of the same environment produced by different people.

Accuracy of Cognitive Maps

The question about accuracy is very important since the quality of the individual map has great influence on the success of journeys or flights. However, it is quite difficult to answer. The problem is the definition of accuracy. Is it total identity between the attributes and arrangements of the spatial environment and the attributes and arrangements of cognitive representations? Then the question is absurd. Such identity is impossible. One function of cognitive mapping is to cope with the staggering volume of spatial information. Humans have neither the processing nor the storage capacity to allow perfect identity between representations and the spatial environment. Cognitive mapping is`, of necessity, selective. There is no one to one correspondence between the spatial environment and its cognitive representations. Shapes and sizes are distorted; spatial relationships are altered; in some areas, detail is impoverished while in others it is augmented.

If accuracy expresses correspondence between the result of this selective process and the “real world“ on which it operates, the question poses two difficulties. What is the real world against which the cognitive map should be compared? Several aspects could be compared like cartographic maps or satellite images. The list of possible replica is almost infinite. So correspondence can only be described regarding the application and information requirements.

The second difficulty in measuring accuracy as correspondence comes from the translation problem, or the attempts to communicate internal cognitive representations to a concrete, external form from which measurements can be taken. Is it possible to judge similarity by comparing data taken from a sketch map with similar data from the cartographic map? If this is an attempt to resolve the accuracy question, the answer is no. People vary widely in simple graphic abilities. Age affects basic manual skills involving eye-hand co-ordination. Both, young people and the very old differ from students. Even discounting this age factor, there is still the problem of different training in both the rationale and manual reproduction of sketch maps. Some people are trained in technical graphic skills. One would expect that the mechanical production and accuracy of the sketch maps would reflect this training. Downs and Stea mention that in a case study a blind graduate student drew a more accurate outline map of the USA than several sighted geography graduate students. The blind student acquired and learned (encoded) the cognitive representation through muscle feedback from touching a Braille outline map of the USA. The sketching (decoding) uses a similar pattern of motor behaviour, involving touch and muscle feedback. The sighted students acquired a representation using an entirely different mode, visual inspection and verbal coding. They lacked the direct interactive experience of the blind student. The medium of translating from an internal or cognitive to an external or physical representation has a major effect on the form of the representation. People vary in their ability to make this translation. So the question of accuracy or correspondence cannot be answered by the comparison of two external representations, as ,in this case, a sketch map and a cartographic map.

The accuracy question is only meaningful if the question is modified: Does a person possess the spatial information and problem-solving strategies necessary to live successfully in a particular spatial environment? Therefore, neither precision nor completeness of representation is necessarily important, but utility is. Downs and Stea concluded that: success in dealing with spatial problems is sufficient testimony to the accuracy of cognitive maps.

Similarity of Cognitive Maps

Just as the question of accuracy was obvious and yet difficult to answer, the question of the similarity of cognitive maps also brings problems with it. The problem does not lie in the meaning of the question. The question is whether two people would produce similar cognitive maps of the same spatial environment. The difficulty lies in the many apparently contradictory answers that can be given. If two people differ in age, for example, their representations will differ as a result of manual skills (in map drawing) or vocabulary and verbal competence. If one were an adult and the other a child, then the different levels of intellectual development would result in different maps. It is also true that experience with the environment would dramatically affect both the arrangement and the contents of the representation. Even if effects of age like experience, skill, and training are controlled, the question of similarity of cognitive maps cannot be answered definitely. The most likely answer to the question is as follows: Parts of people’s cognitive maps are common to all or most members of a large group of people; parts are common to a subgroup of people; and still other parts are unique to each person. These variations in similarity result from three interlocking variables:

- the scale of the spatial environment
- the source of the information about that environment
- the location of the person doing the representation.

1.4.3 Cognition in Virtual Environments

The field of psychology has endeavoured over the past 100 years to describe how man relates to his environment. What we find are deep analytical discussions concerning the physical environment and man's place in it; how we extract information from the environment; and how we process that information and eventually act on it. Now along comes the notion of a "virtual" environment - and all the rules change. All the assumptions psychologists have made concerning the characteristics and features of the environment are now invalid or at least demand re-evaluation (Figure 24). Much of what we are doing here is re-evaluating a body of research within the context of a new medium. How are virtual environments different from real environments and what behavioural repercussions does this difference have on human activity and the ability to perform real tasks? [Dar97]

In psychological applications virtual environments are used as a tool for experimentation. While “large scale environment“ experiments in the real world are difficult to design and control, everything can be controlled in a virtual environment. Global as well as local landmarks can be set, route mapping can be supported and maps can be easily derived. Today psychologists, scientific engineers and others try to evaluate whether behaviour in real and virtual environments is comparable. If this is shown for navigational behaviour, Virtual Reality will be accepted as an adequate research tool.

Research on spatial problem solving could be transferred to an experiment in a virtual environment. Hypothesis could be verified or falsified and results could be re-transferred to the real environment. Advantages like flexibility, controllability and validity would make this method an important tool (Figure 25).

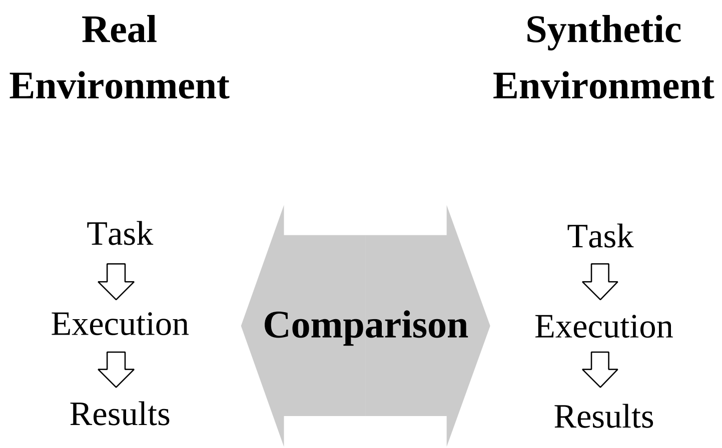


Figure 24 Can Cognitive Knowledge be applied on Virtual Environments?

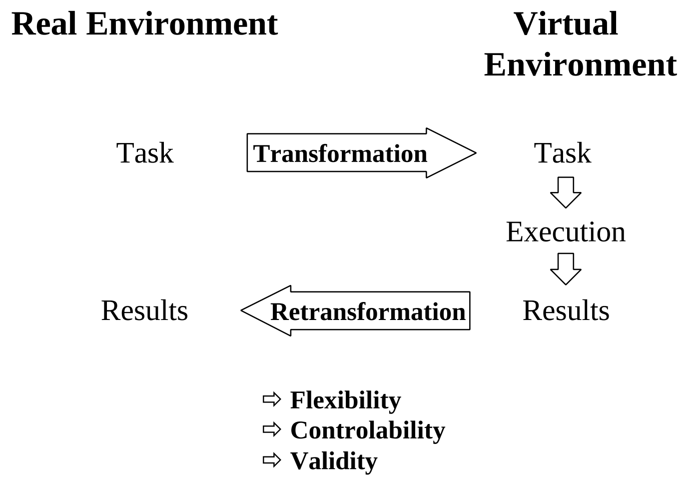


Figure 25 Research in Virtual Environments

In this application (CFGD), virtual environment is used to mirror the real world since it cannot be perceived in some meteorological conditions. So research on navigation in virtual environment is used not only to apply the results in reality but also in virtual environments. Validity of knowledge on spatial behaviour in real as well as in virtual or synthetic environments will help analysing the CFGD. The problem of familiarisation in synthetic environments can be transferred to the real environment, analysed with existing knowledge on cognition and re-transferred to the synthetic environment. This method should provide design principles that can be implemented into the application and validated in experiments.

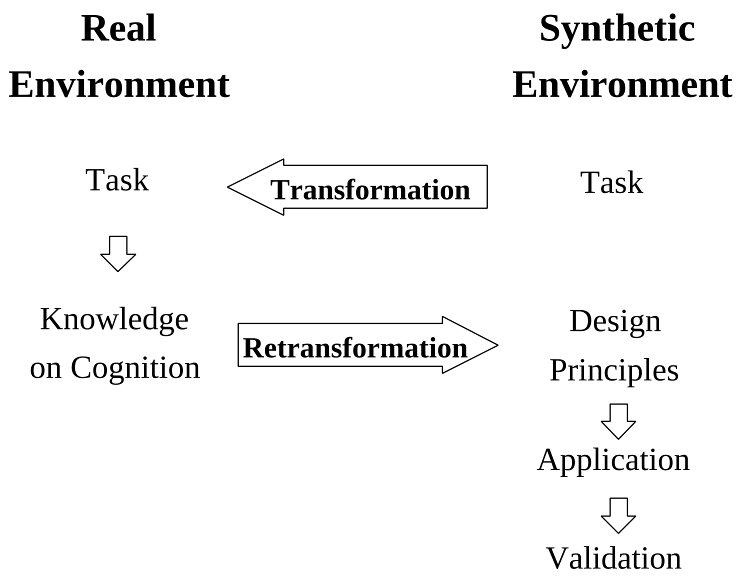


Figure 26 Application and Validation of Knowledge on Cognition in Virtual Environments

Darken has shown in his dissertation that spatial problem solving in synthetic environments is based on the same principles as in reality. He concluded [Dar97]:

1. Without a source of directional information, disorientation will inhibit both wayfinding performance and spatial knowledge acquisition.
2. A large world with no explicit structure is difficult, if not impossible, to search exhaustively. This was shown by repeated reacquisition behaviour in the control treatment.
3. A conceptual coordinate system is often imposed on the world to act as a divider. This is a side-effect of not being able to divide the world explicitly. A structure must be imposed on the world if an organised, exhaustive search is to be attempted.
4. Experimental observation supports the notion that path following is a natural spatial behaviour. Subjects frequently used features such as coastlines or grid lines as if they were paths.
5. A map allows for optimisation of search strategies. This is because it can be considered a supplement to survey knowledge.
6. Dead reckoning was observed to be an intuitive and natural part of navigation; all subjects exhibited this behaviour even though frequently unaware of it. The ability to infer position from a past location and constant velocity over time, while sometimes complex in reality appears to be more easily understood and implemented in virtual spaces.

This proves the validity of the idea that spatial behaviour in real as well as in synthetic environments is based on the same principles. Further on, the problems of cognition in the synthetic environment of the CFGD will be dealt with as a problem in the real environment.

1.4.4 Problem Analysis of Cavok Flight Guidance Displays

Taking the psychological aspects into account, different perceptual and cognitive problems appear. In this chapter those problems concerning perception and cognition will be mentioned and analysed in detail. They will be the basis for proposed improvements to the CFGD. The analysis of the state of the art of the CFGD was described in chapter 1.3.4.1 and Kaufhold's dissertation[Kau98[40]].

A problem we have to face is the fact that perception is subjective and based on the experience and expectation of each individual. The first problem, for example, is the blurred depiction of the terrain, especially in the ND. If you see the terrain for the first time you will be impressed by how vivid it is. But as soon as you have seen a better depiction you will recognise blur. For this reason the problems will be explained relative to intermediate results of this thesis. The necessary way of data processing will be mentioned later.

1.4.4.1 Perceptive Analysis

In this chapter visual deficiencies will be mentioned. On the one hand, these deficiencies are obvious when comparing the current and the new terrain depiction. The new terrain just looks sharper. On the other hand, the problems mentioned here have significant influence on cognition as you will see later on.

Blurred Depiction

Problem Description

Looking at the Cavok displays and especially the navigation display, the perception of topography is possible. Terrain elevation is colour coded and shading improves the vivid impression. Figure 27 shows the “Dachsteingebirge” in Austria in the conventional depiction. An intermediate result of the new terrain depiction is shown in Figure 28. If you compare both figures you will have the impression of blur or the conventional depiction being out of focus. Terrain contours are washed out. On the one hand, this results in an uncomfortable perception; on the other hand, the perceived dimension of this 3000 m high mountain range is misleading. Gradients are washed out and make you perceive a less elevated environment. The conventional depiction is close to the first shaded maps created in the last century. Mountains in these early maps appeared like dunes and molehills.

Figure 27 Conventional Depiction

Figure 28 Intermediate Result

Analysis

For the analysis of this problem another example will be helpful. In Figure 29 the Feldberg mountain near Frankfurt is depicted in the conventional way. You can see a pixelised transition between light and dark surfaces. Additionally you will detect the blur in this transition area. If you look at Figure 30 you will see how the Feldberg was generated.

The DEM consists of equidistant elevation data. 10” is the separation which equals about 300m. Since the raster size is bigger than the resolution of the presentation medium, the observer has the impression of stairs. But this is not the reason for blur. If you carefully detect the transition phase you will see the wash-out effect between each colour change.

As mentioned above, there are two image generation techniques -flat shading and gouraud shading. While flat shaded triangles have one colour, gouraud shading interpolates the surface colour between the colour of the vertices. Figure 31 shows the terrain grid and an isohypse which connects points of the same elevation. If terrain above this line should be coded in black for example and in white below this line the flat shaded triangles would look like this. As you will recognise, this depiction looks very synthetic and irregular. The gouraud shading depiction Kaufhold used is much better. Figure 32 shows the same situation in gouraud shaded depiction.

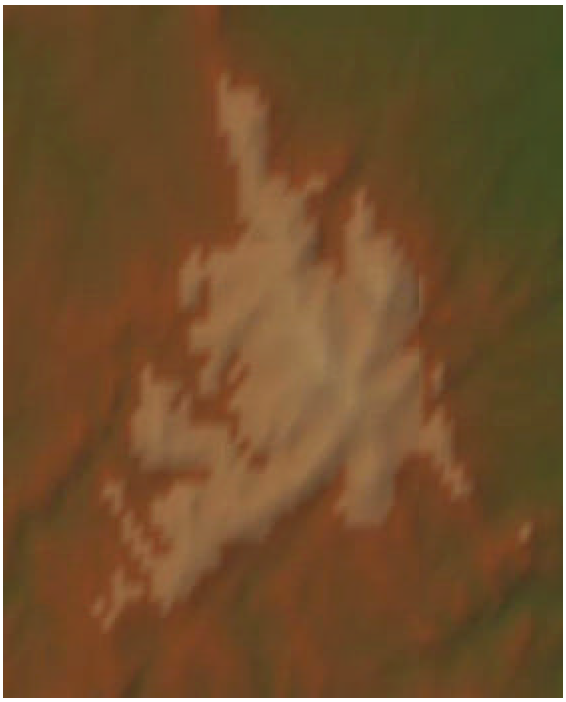


Figure 29 Feldberg Mountain

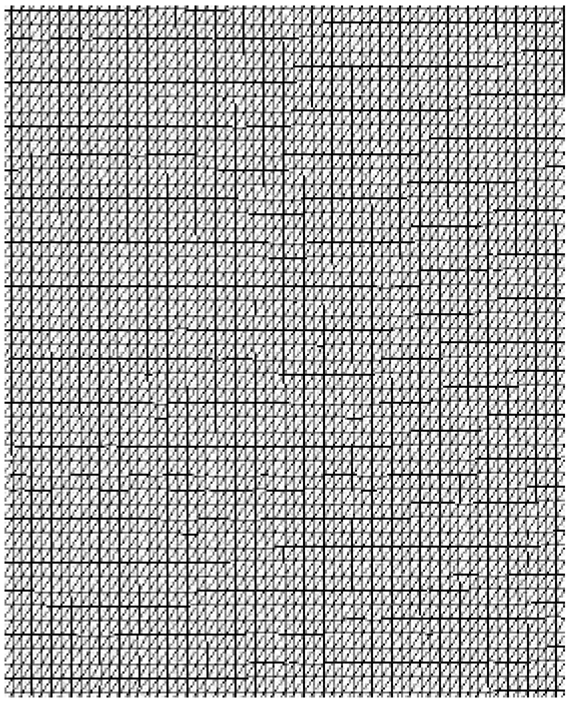


Figure 30 Wire frame

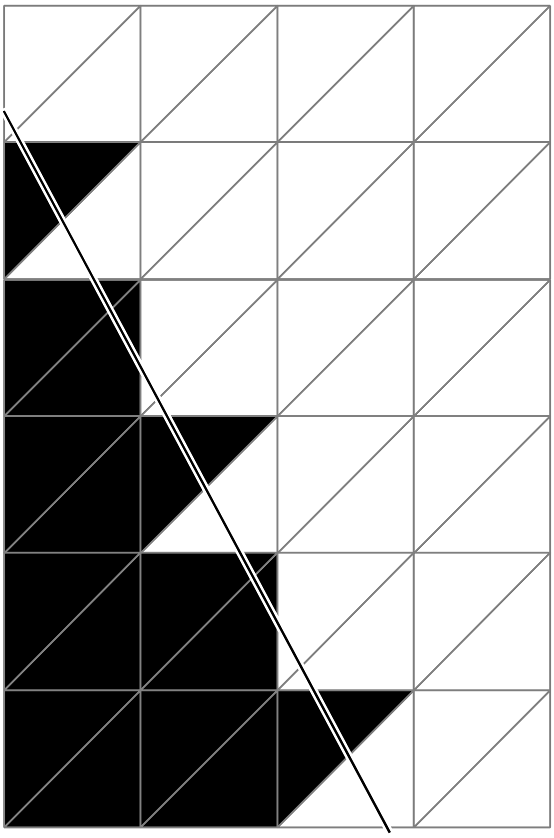


Figure 31 Flat Shading

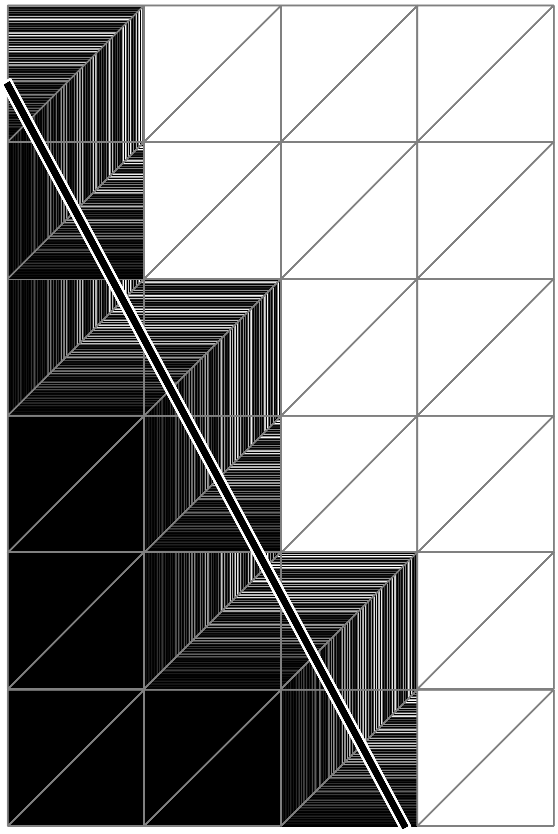


Figure 32 Gouraud Shading

Of course the colour change from black to white is extreme, but it helps to illustrate the visual effects. The transition looks much smoother than the flat shaded one, but you get the impression of blur. This is reduced if you zoom out so that the colour change becomes smoother, but you will recognise it anyway as you have seen in Figure 27 to Figure 29. The same effect occurs with shading. Negative effects on cognition will be mentioned in chapter 1.4.4.2.

Distorted Depiction

As mentioned in the last chapter, raster resolution may be higher than necessary for terrain depiction. Decimation of this data may be realised in two ways. Skipping some points regularly and creating a new database with lower resolution is the most simple way. Instead of simply skipping points, creating new data including the highest elevation is better with regard to safety aspects. The advantages are that errors become simple and controllable and that there is a the possibility of rendering meshes as mentioned above. The disadvantage is the problem of zooming that is typical for these **P**seudo **V**ector **D**ata (PVD).

Polygonal simplification and generating a **T**riangulated **I**rregular **N**etwork (TIN) from original data is the second possibility.

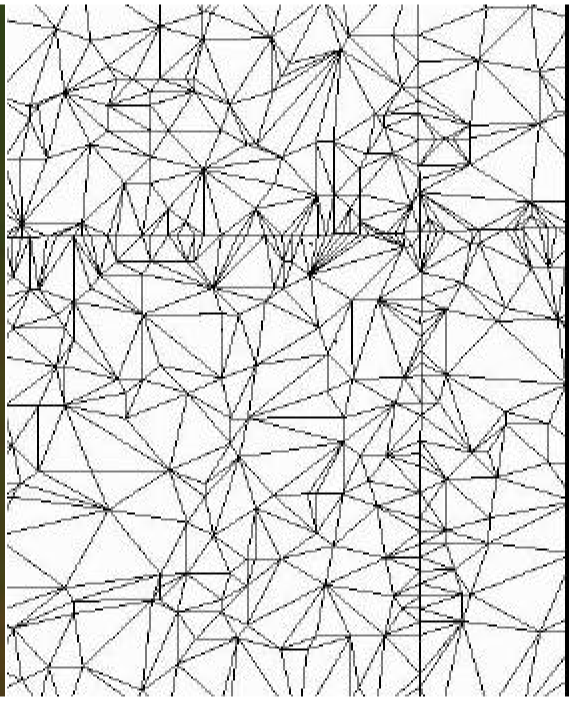


Figure 33 Polygonal Simplification Figure 34 Wire Frame Depiction

Polygonal simplification is the act of transforming a three-dimensional polygonal model into a simpler version. It reduces the number of polygons needed to represent a model while trying to retain a good approximation of the original shape and appearance.

Problem Description

Figure 33 shows the Feldberg mountain after a process of polygonal simplification. The process of polygonal simplification will be explained after the description of the influence on perception and cognition.

For a comparison of Figure 33 with Figure 29, you need good will, otherwise you will not see any similarity. Blur is even more conspicuous than in the non-simplified version. These negative effects of polygonal simplification totally distort the topological characteristics which has strong influence on cognition, as mentioned later.

Analysis

Polygons are the most popular primitive drawing in computer graphics. Specialised graphics hardware can render them very quickly, and polygons can approximate any model. Unfortunately, accurately representing a three-dimensional model often requires a large number of polygons. For example, a smooth looking sphere can easily require several thousand polygons. Current high-end computer graphics systems can render approximately a million polygons per second. If an application requires a 30 frames per second update, then it can draw roughly 30,000 or fewer polygons in one frame. Although this number seems large, an accurate representation of one three-dimensional model can easily contain 30,000 polygons. Nowadays, a million polygon scene is not extraordinary, and the day of the first billion polygon model rapidly approaches.

Computer graphics hardware will be under pressure to keep up with this growth in model complexity. For every computer graphics system, there exist models complex enough to bring its performance to a crawl. Polygonal simplification attempts to narrow this discrepancy between model complexity and hardware performance. Suppose a graphics system or application renders a scene of a house in which a 10,000 polygon chair is distant from the viewer. Since the chair is far away, it spans only a few pixels in the final image. If the application renders all 10,000 polygons, then each vertex in the model transforms to the same few pixels and each polygon rasterises to the same few pixels as well. In this case, the vertex processing becomes the rendering bottleneck and not the polygon rasterisation. Certainly, rendering all these polygons is excessive. Instead, suppose the system substitutes a 100 polygon simplified chair for the original model in the scene. Not only does the resulting image look roughly the same as the original, but the application achieves a 9,900 polygon performance gain. Instead of having one simplified representation of the chair, suppose there exist several gradations of simplified chairs. The system substitutes for the original an 8,000 polygon model when the viewer is a certain distance away from the chair, a 5,000 polygon chair when the viewer is even further away, and a 100 polygon chair when the viewer is extremely distant. Ideally, polygonal simplification enables the rendering of the fewest number of polygons possible to represent an object while ensuring the same image quality as the original. This chapter emphasises increased rendering performance, but polygonal simplification provides other benefits. A three-dimensional model requires a large amount of storage, but simplification reduces these requirements if a system permits model degradation. This storage reduction helps speedup the transmission of large models over networks. Simplification also increases the efficiency of computationally intensive problems such as radiosity calculation, ray tracing, and collision detection [Eri96[58]].

At Darmstadt University we use a geometry removal algorithm, created by Schroeder [Sch92[59]], which performs well on models produced by the Marching Cubes algorithm. Since Marching Cubes produces a large number of polygons, simplification is often a desirable post-processing tool. The vertices of the simplified model are a subset of the original. The user specifies a distance error term. The algorithm can remove a vertex only if it is within this distance between the approximation and its original local topology. Unfortunately, this method calculates distance error using the current simplified model and the model of the previous iteration. To be more accurate, it must compare the current simplified model with the original, but this requirement is not fulfilled for the polygonal simplification currently used for the CFGD.

An iteration of this algorithm initially picks a vertex in the model. Using information from adjacent faces, it characterises the local vertex geometry and topology. It considers the vertex for removal only if this operation preserves local topology. At the chosen vertex, the algorithm evaluates the decimation criteria. It calculates the distance from the vertex to the average plane of its adjacent vertices. If this distance is less than the user-specified error term, it removes the vertex. The algorithm removes the vertex and a hole appears. It uses a technique called loop splitting to triangulate the hole. Loop splitting attempts to find the split across a polygon that produces triangles with optimal aspect ratios. This algorithm iterates until there are no more vertices that meet the decimation criteria. Figure 34 demonstrates one iteration of the algorithm.

Skipping points of the original data within a tolerance of gradient changes or generated errors is a method for data reduction under safety critical aspects. The necessary algorithms are complex and difficult to control. Loss of peaks, for example, has to be avoided at all events. Another problem is the connection of tiles. Resolution at tile edges has to be increased in order to avoid gaps, as you can also see in Figure 34. Rendering performance, on the other hand, is reduced significantly since meshes cannot be rendered anymore. Every point of irregular triangles has to be transformed in the geometry engine thus reaching only one third of the performance with a TIN compared to regular data.

Of course, decimation implies a loss of visual quality meaning a loss of characteristics. If you look at Figure 29 you can see the Feldberg Mountain near Frankfurt Airport with an elevation of 2884ft. Terrain is depicted from 10” PVD, and you can still see the bitmap problem. However, this mountain has its characteristics.

Figure 33 shows the Feldberg Mountain decimated to a TIN. There is a significant loss of characteristics, even if the elevation failure may be small. Compared to VR applications, the terrain decimation is much more visible. In VR, for example, most features are textured, reducing the necessary visual quality of geometry. If you map a satellite texture onto the decimated and the non-decimated terrain as you could do for a simulator visual, you will not recognise a difference. Thus, visual quality or characteristic is realised by texture. For a non-textured application, polygonal simplification as it is currently applied is of no use. [Hel99a[60]]

Changing Characteristic

Problem Description

Figure 35 is the conventional visualisation of the Hochvogel mountain in the German Alps. Each picture shows the mountain at a different orientation. While the observer expects the light source to come from the upper left-hand corner of the image or depiction, the heading dependent orientation of the terrain changes its characteristics during turns.

Even deliberate examination does not enable you to decide if these four pictures really represent the same mountain. This not only causes a feeling of uneasiness because you do not recognise common structures, but it also has influence on cognition which will be mentioned in the cognitive analysis chapter.

As mentioned above, the ND is heading-up oriented. Heading-up means that the depicted terrain is always oriented to the present direction of the aircraft. For planning purposes a North-up depiction may be selected.

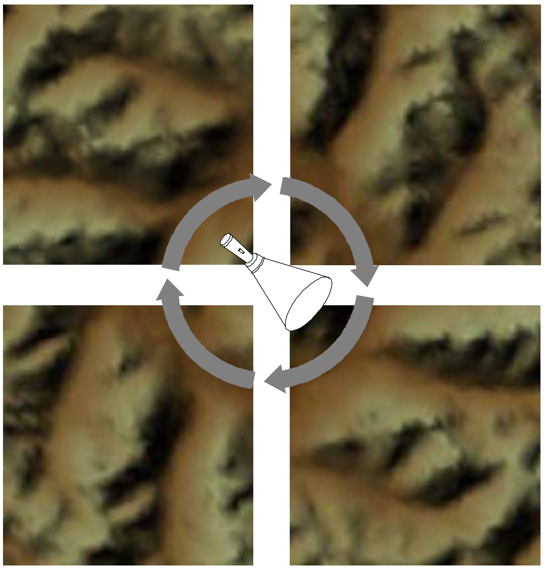


Figure 35 Hochvogel Mountain

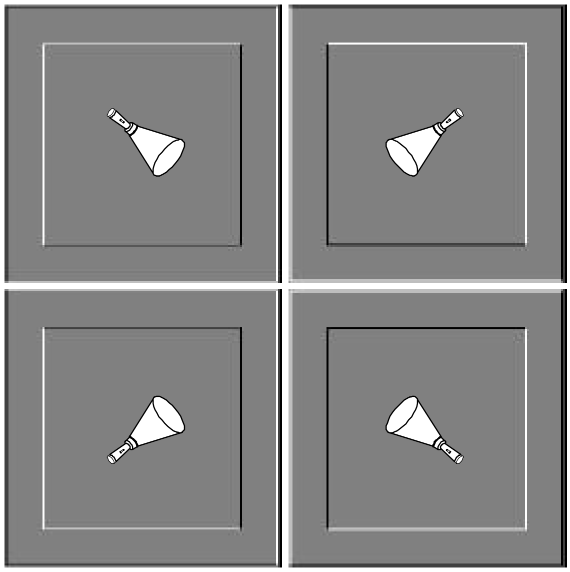


Figure 36 Effects of rotating Light Source

Analysis

Already in the first topographic maps, cartographers have found that humans expect a light source to come from the upper left-hand direction. This important technique of shading terrain for a more natural and vivid perception was also used by Kaufhold. He implemented a light source on the upper left corner of the navigation display. So the shading is not geographically but display fixed.

As mentioned above the lighting direction now depends on the heading and the selected mode of the ND. The effect of a non-static light source can be seen in Figure 36.

While the light on the upper left-hand corner makes the square look elevated over the frame, light on the lower right-hand corner makes the square appear lower than the frame. For the two other buttons, it depends on the individual whether or not they are elevated. Some individuals can even switch between both perceptions.

This inversion can also be experienced if you rotate this book and look at Figure 40. Valleys will appear as mountains and vice versa.

But this description does not explain why the topographic characteristic is changed so significantly that the rotating Hochvogel mountain cannot be recognised. Figure 37 shows the raw data used for the terrain visualisation. This wire frame depiction emphasises the equidistant lattice between the measured coordinates. Colour coding is based on a colour table which defines one value for each elevation. With one value for each vertice, the terrain is gouraud shaded as mentioned above. Figure 38, for example, is the depiction of the Schwangau without any shading. Topographic characteristics is only obtained by the elevation coding. This depiction is independent from any heading or display orientation and recognition should be easy. The lighting model in contrast changes its characteristics with every heading change since ridgelines stand out or

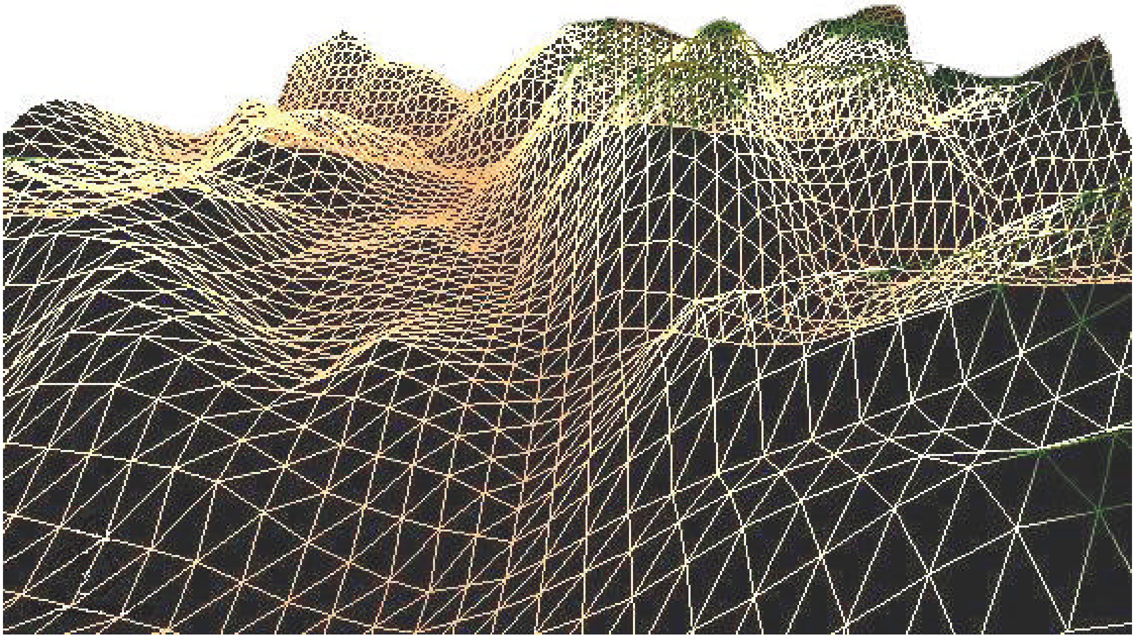
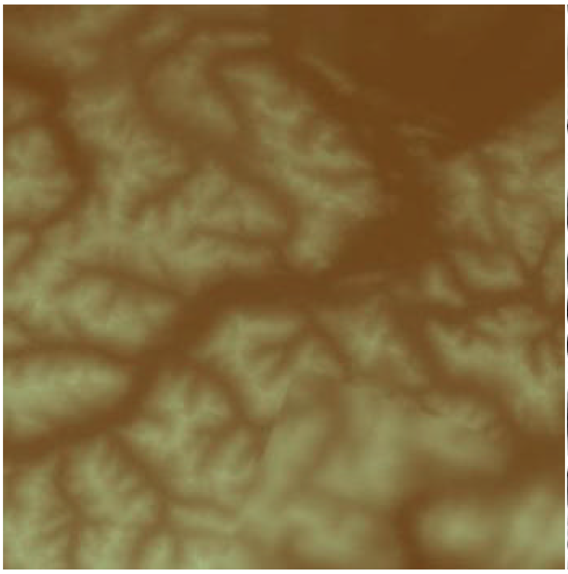


Figure 37 Digital Elevation Model

disappear depending on their orientation relative to the light source. Figure 39 shows the same area shaded from the upper left –hand corner with no supplemental elevation coding.

The conventional terrain depiction is merged from both figures. Obviously the heading dependent lighting dominates the elevation coding. This is the reason why the depiction of the Hochvogel mountain changes its characteristics.



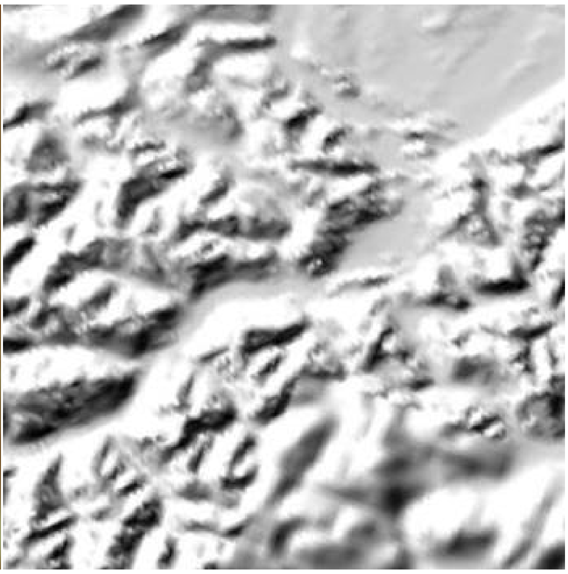


Figure 38 Colour Coded Terrain Depiction Figure 39 Shaded Terrain

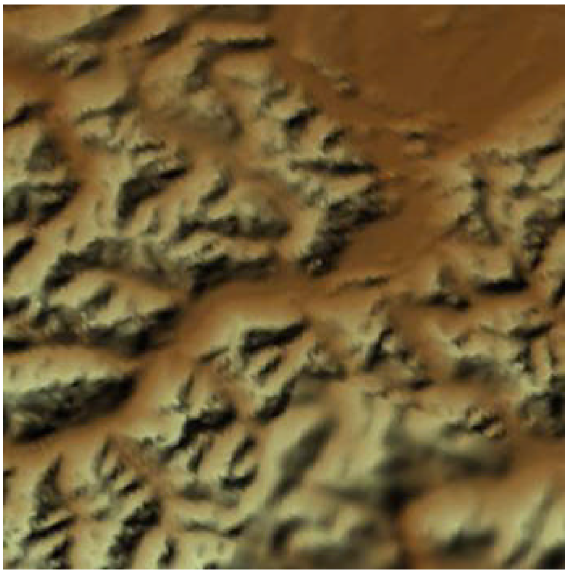


Figure 40 Colour coded and shaded Terrain Depiction

Limited Zoom Ranges

Problem Description

In chapter 1.4.4.1, the pixelised depiction has already been mentioned. Depending on the current flight phase and, thus, required information, the pilot has the possibility of changing the scale of the ND. Compared to conventional paper charts, this is a significant advantage of electronic devices. On the other hand, this requires qualities paper charts did not have to have. If the navigation display is zoomed in to a certain level the depiction appears in steps and pixels can be distinguished.

Analysis

Since the data resolution could be adapted to the printed scale, resolution was as high as necessary and as low as possible for each chart. For the terrain depiction on the display, the data resolution for small scales (small range) may be adapted, but the necessary rendering performance is not sufficient for higher scales (high ranges). This problem is surprising, since visualisation is based on vector graphics and not on bitmaps. From the data storage point of view, these data are raster data even if the depiction is based on vector graphics. We know the visual difference between raster and vector data from drawings based on pixels like bitmaps or vector graphics like CorelDraw. Disadvantages of bitmap images are well known: first, if you zoom in, the raster image is pixelised as soon as the image resolution is less than the resolution of the presentation media; second, if you zoom out, the data size is bigger than necessary. So the pixel size, thus resolution, should be adapted to the media resolution and zooming should not be required (Figure 29).

In short: ***Each pixel on the presentation media should be rendered from two triangles.***

As mentioned above, the DEM is a raster model from the data storage point of view. Rendering is based on vector graphics, but the depiction has the conventional raster characteristic. Thus, I would like to call the depiction based on any equidistant lattices Pseudo Vector Depiction.

Like the other problems in chapter 1.1.1.1, this also significantly influences the necessary workload for the perception of topography. Easy recognition is very difficult or even impossible.

1.4.4.2 Cognitive Analysis

In the next chapter, the influence of these deficiencies on cognition will be mentioned and analysed as well.

Cognitive processes require perception as information input. For this reason, problems concerning perception were mentioned first and their influence on the cognitive process will be explained in this chapter. A psychological basis has been established and the problem of familiarisation may now be analysed.

Problem Description

The motivation of this thesis was to improve perception and cognition, since familiarisation with synthetic environments is very difficult and sometimes even impossible. Repeated fly-bys did not result in a feeling of being familiar with the environment as pilots know it from everyday experience. First, this results in a higher mental effort since situation analysis takes longer in an unknown environment. Secondly, the pilot has the impression that his skills are not sufficient for this task.

Analysis

For a better understanding and precise description, you have to analyse the mental process. The model of the brain shown in Figure 41 is a very abstract one and shows the process of perception and cognition. In the right part there is a stimulus in the visual field of a subject. This stimulus, a cat for example, is transferred into consciousness via the process of perception. Now the subject is able to see the cat. Perceived information is filtered and transferred into memory if it passes the filter. In the memory, the subject stores information about this cat like colour, shape or behaviour. If the cat has left the visual field, the subject is still able to get a mental representation of this cat by the process of reminiscence. The cat is back in his consciousness without seeing it again. Surprisingly, he is even able to get a mental representation of the backside of the cat even if he has never seen it.

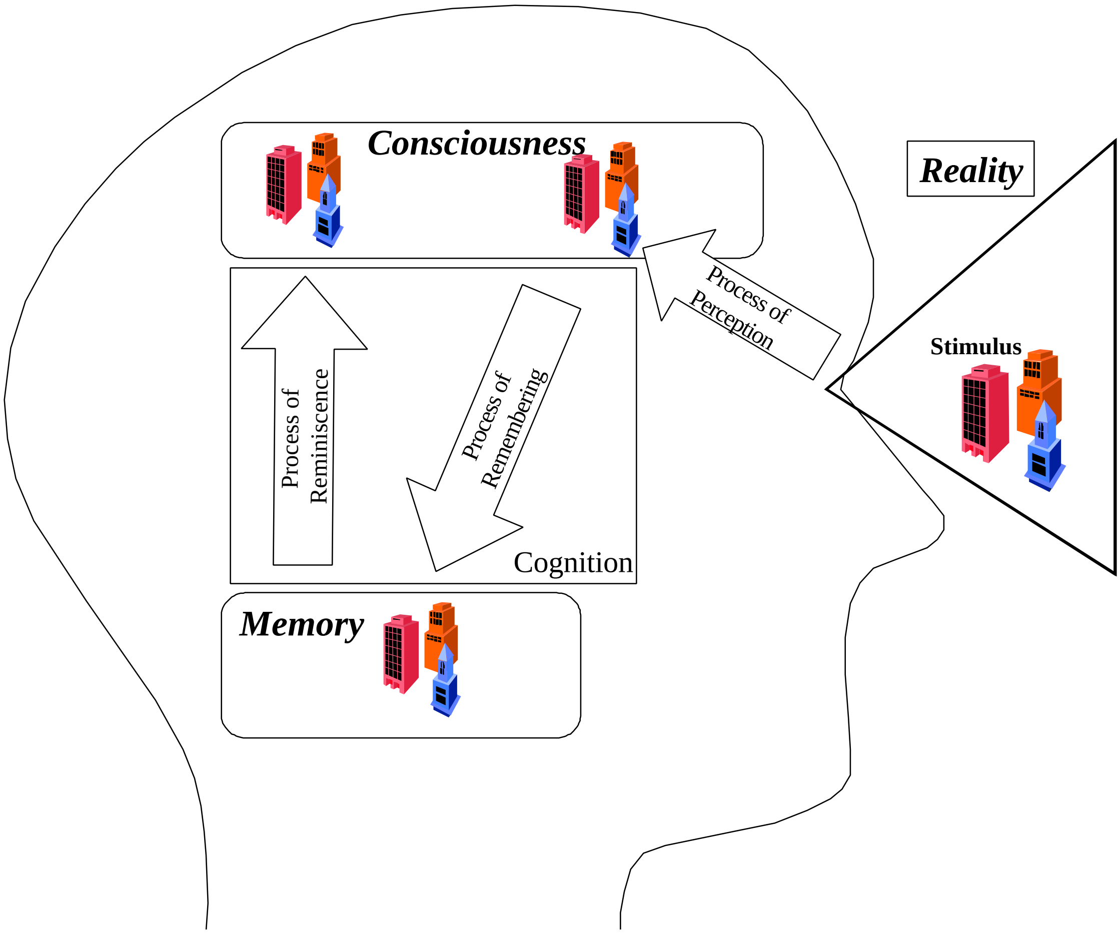


Figure 41 Process of Perception and Cognition

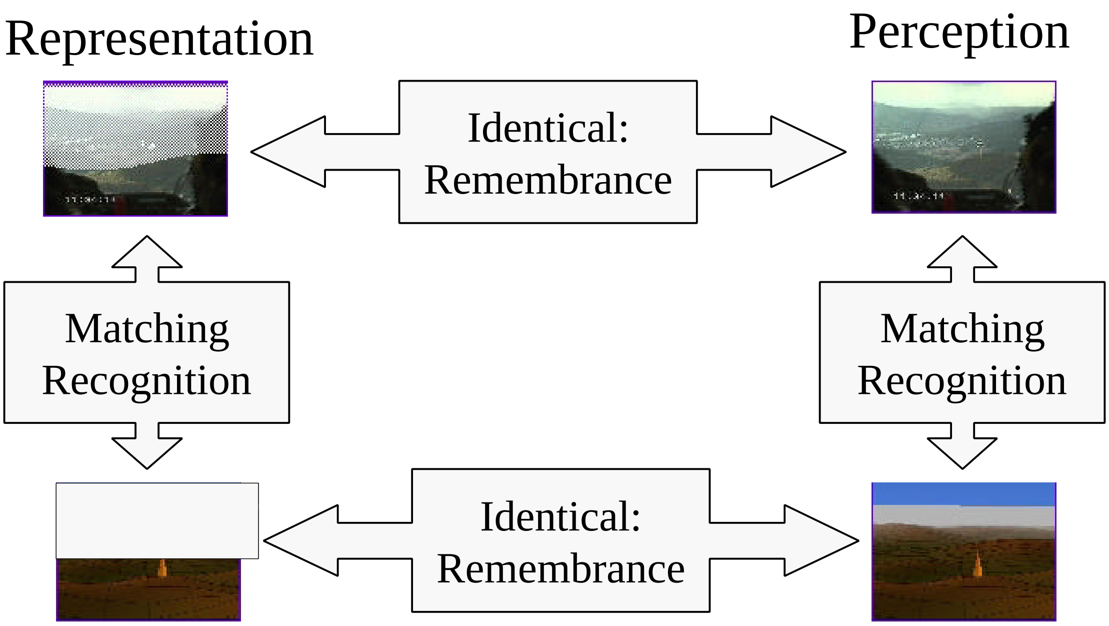


Figure 42 Processes in Consciousness

What happens in consciousness if a pilot flies a SVS equipped aircraft? Figure 42 shows a magnification of the consciousness. In the right part, there is the perception of the outside view and the perception of the SVS PFD. As mentioned above Kaufhold showed that terrain is matching if both perceptions are comparable by the subject. If we look at the mental representation of the environment, we know from everyday experience that we have mental representations of our home or office. When we enter our office we have the mental representation as well as the perception, and if they are identical we have found our way. At this point, it should be mentioned that the mental representation is never completely accurate because of the limited amount of information that can be stored.

The problem of not getting familiar with the synthetic environment can be analysed by looking at the lower part of Figure 42. It was already mentioned that it is very difficult to remember a synthetic environment, as we called it before. Now we can see what causes this problem. There is a perception of the synthetic environment when we look at the SVS display, but we have no mental representation based on experience. If we look back at the process of perception and cognition, two reasons are conceivable. The first reason could be that we memorise the synthetic environment, but the process of reminiscence works incorrectly. The other reason might be that the process of remembering does not create spatial knowledge. Both reasons are surprising since the processes operate correctly in a real environment. Additionally, Darken [Dar97[44]] has shown that these processes work in a virtual environment as well. So this is not a problem in principle but a problem very specific to this kind of terrain depiction used for the CFGD.

We have to distinguish between free recall, or a priori recall, and recognition, or a posteriori, recall. Free recall, as we usually know it from exams, is more difficult than recognition supported by hints like multiple choice questions. Since we found out that mental representations of synthetic environment are not present even if we have a perception of this environment, I would like to make this hypothesis:

In my opinion, the process of remembering works insufficiently in the Cavok synthetic environment. This hypothesis will be the basis for further research.

Missing Landmarks

If we look back to Figure 23, the sensorimotor level is the first level of spatial knowledge. It consists of observations like views, actions and sequences and is called landmark knowledge. The next levels like procedural, topological and metric knowledge require landmark knowledge as a base. The choice of landmarks depends on the specific application as well as on individual preferences.

Typical landmarks when used by pilots regarding terrain are for example:

- *Topography*: striking peaks and ridge lines
- *Cultivation*: fields, forests, moors, meadows, opencast mining, etc.
- *Cultural information*: towers, castles, railways, highways, etc.

These landmarks should be integrated into the SVS for cognitive mapping purposes. However, in order to declutter the SVS only mandatory information is presented. Mandatory, for example, is that the pilot presently approaching an airport with two parallel runways and the left one is selected. The existence of a forest or striking ridge line far from the threshold is not of direct interest to the pilot. However, there are no unique places in the synthetic environment and users are not able to perceive landmarks. The question is: How can we present necessary information in a manner that supports landmark acquisition and thus cognitive mapping?

Summary of Problem Analysis

On the one hand there is no depiction of database features that could be used as landmarks and thus provide cognitive mapping. On the other hand the shaded terrain is very difficult to map since the direction of the light source is constantly changing. The only relief specific information that could be mentally mapped is the colour coded terrain elevation.

2 Design

2.1 Maps, Charts and Electronic Devices

Mapping involves the use of a set of operations which translate information taken from the spatial environment into an organised representation so that at a later date, this representation will be useful to us.

Representations can be stored either externally or internally. External representations include such physical things as an apron chart that help us to find a parking position. Each of these external representations has a concrete, material form of existence: paper and ink, or computer hard disks. In contrast, internal representations are stored in our memories, and exist somewhere in our brains. The next chapter will exclusively focus on external representations.

2.1.1 Historical Background

As commonly understood, certain distinctions have developed between maps and charts. Maps are generally topographical and are applied for many purposes. Charts, on the other hand, are nautical or aeronautical and are used only for navigation of one kind or another. Maps tend to have a more permanent nature, while charts may be annotated and then discarded or be subject to periodic revision and replacement as the data which they display change.

The technology used in the design and production of maps and charts is called cartography. It was about 100 years ago that suggestions were first made on how maps could be annotated to assist air navigation, and at that time the maps were based only on the experience of ballooning. The first aviation chart was probably produced early this century in Germany, but a systematic and professional application of Human Factors to this field of documentation has been notably lacking since then. In general, it can be said that the needs of the user did not have sufficient influence on either the content or the appearance of most aeronautical maps and charts.

There seem to be two basic reasons for this neglect. Firstly, the design of maps and charts is an activity involving long tradition. The responsibility for the design lies in the hands of specialised cartographers, and so the designs have inadequate input from psychologists, engineers or the users of the materials. Many of the colour conventions of 19th Century land mapping were followed in aviation cartography without much serious consideration of their merits [Tay85[61]]. And secondly, research into the Human Factors of maps and charts is both complicated and expensive. When attempts to apply Human Factors data have been made they have often not gone beyond the application of the general principles of displays, an unsafe and frequently inappropriate practice[Haw87[62]].

2.1.2 Media

The paper basis of conventional maps and charts not only provides flexibility in that they can be folded to almost any size or shape, but it allows them to be easily annotated. This makes them very portable and permits convenient storage. Since they are paper, they are inexpensive and easily replaceable. However, they have disadvantages in the operational environment. Consulting a conventional chart while at the same time instrument flying in a complex terminal area poses difficulties due to the location of the chart, its insufficient illumination (at night), the lack of selectivity in the information displayed, the fixed orientation and the lack of any indication of the aircraft's continuous position on the chart. Progressively, new technology has been applied to overcome some of these difficulties as well as to provide entirely new possibilities unavailable on conventional charts.

Perhaps electromechanical instruments such as HSI may be seen as a primitive form of map display. But in a more truly cartographic form, development of automatic chart displays has tended to follow three routes. Direct view map displays such as Decca Navigator take the form of a strip map, moved on rollers, with a cursor indicating the aircraft position. Optically projected map displays consist of a microfilm transparency of an actual map projected from behind onto a screen, with a symbol to represent the aircraft. Electronic map displays have replaced these two earlier forms of moving maps and are more reliable, more accurate and more flexible in display content.

Many of the Human Factor aspects of conventional maps and charts discussed here are also applicable to these newer automatic devices, but each new display technology brings with it new problems which must be solved.

The cockpit environment with varying illumination is very demanding for hardware design. In daylight conditions glare requires high brightness and contrast. Conventional Cathode Ray Tubes (CRT) work in stroke mode which allows higher brightness than raster based images. Liquid Crystal Displays (LCD) are state of the art for several applications and the Boeing 777 was the first LCD equipped transport aircraft. Brightness and contrast of LCD is especially critical while resolution equals standard computer monitors.

2.2 Cartographic Design Process

The first stage of the mapping process involves map creation or encoding; the second stage involves map reading or decoding. Thus the process of mapping consists of two parts, map creation and map-reading, while the product of map creation is the organised representation which may be stored internal or external to the individual.

The obvious question is: How do people create and read maps? When considering the presentation of information about a particular town, one finds sets of rules and instructions for both map creation and map reading. In the case of the street map, for example, someone has to decide what part of the city to include, what places to emphasise, and what streets to name. All of these decisions are based on rules for map creation. On the other hand, the rules for following a sequentially described path are different from finding a place using a map. These differences should not come as a surprise, because representations are functionally similar but formally different.

If one thinks of guidelines for map creation and map-reading, there are four major questions to consider:

1. What are we interested in representing? *Information requirement*
2. What viewpoint or perspective are we taking? *Visualisation parameters*
3. What scale should we use for the representation? *Scale*
4. How do we construct the representation? *Symbolisation*

A decision on each of these questions leads to a set of rules for map creation. We must also know the same set of rules to read that particular representation. We can understand these decisions if we look more closely at two representations: the apron chart and the controllers instructions for reaching the parking position. In producing the apron chart, you have to decide upon its purpose. Who is it for? Will it be for pilots or follow me drivers? The answer to this question is crucial since it determines for whom the representation is useful, and what type of spatial problem it can assist in solving. The purpose of the map also leads to the answer of the remaining three questions. In the case of apron charts, the decision about perspective follows specific conventions. Cartographic maps are usually based on a vertical or bird's-eye perspective. Directly linked with the purpose and perspective is the question concerning the scales of the apron chart. Scale is simply a measure of the size of the representation relative to the size of the environment being represented. The scale depends on what part of the spatial environment is of interest. In the environmental context discussed here, representations are always smaller than the environments represented. However, variations in scale are an important consideration. The choice leads to a trade-off between the detail that one can include and the area that can be represented. In an apron chart at one scale, individual parking positions can be presented, while in a smaller scale a much larger area might be presented. However with the smaller scale, you would not be able to distinguish particular gates.

Finally, the symbols have to be chosen. If you want to indicate a railway station or navigation aid, how should you present it? Once again conventions help to decide. This stage of mapping involves the selection of symbols that will externally stand for the original object in the spatial environment.

The same four questions have to be answered by the controller when giving taxi instructions. The purpose is to guide pilots from stop bar to stop bar and from taxiway to taxiway. The perspective is "eye level", that of the pilot in his cockpit. The representation concentrates on signs visible at eye level. In terms of scale, the instructions are much shorter than the route, and, more importantly, organised in a certain order, while the apron is not. The symbols used are verbal.

Thus, the set of rules involved in both stages of representing an environment (map creation and map-reading) is the result of answering the four questions about purpose, perspective, scale and symbolisation. All representations share these common features, although the results of specific decisions give the representation its particular format. To emphasise this point, the specific set of rules for creating and reading a particular representation or map will be called a signature. Representations of the spatial environment also have a signature. The typical signature of a cartographic map is the use of a vertical perspective, with a scale of 1:50.000 and with blue lines for rivers, red areas for towns and so on. The signature is the set of rules which controls the process of map creation and map–reading.

2.2.1 Contents

Besides the distinction between maps and charts cartographers classify two major types of cartographic representations. Topographic maps include topographic situation, waters, terrain shapes and cultivation. In contrast to this, thematic maps represent a certain topic like the climate for example. The border between both types cannot be defined exactly. On the one hand, each topographic map might include thematic subjects like political borders, but they are not the main purpose of this map. On the other hand, only a few distinct and emphasised objects make a topographic map a thematic map.

Frequently, topographic maps are the basis for thematic maps.

The topographic background of thematic maps serves as a geometric reference and an easier understanding of the theme. In general, the topographic background should be legible, but should stand back behind the thematic representation. Four different designs are possible for the creation of a topographic background:

1. The topographic background is a conventional map. It is unmodified, and thematic information is overlaid.
2. Slight modifications are processed like decreased colour coding and removal of objects like forests and cultivation. This increases the contrast and emphasises the thematic topic.
3. The topographic background is especially designed for the specific application and scale. Usually this is the best solution, enabling adapted generalisation and ergonomic design. Of course this method requires the most effort.
4. Satellite images or aerial views are used as background. Like method two, reduction of colour saturation can increase contrast.

Topographic Maps

In cartography, topographic maps are called real topographic maps if they represent topography completely and accurately. Down to a scale of 1:300.000 this requirement is realisable, while small scales require generalisation implying topographic errors. These maps are called chorologic or physical maps. Characteristics are scale based renunciation of details, improving the representation of geographic relations. Some examples are general maps (1:1 Mio –1:10 Mio) and continental maps (>1:10 Mio).

Terrain Representation
Terrain or relief is defined as the boundary surface of soil (lithosphere) and air (atmosphere) or water (hydrosphere) in its three dimensional shape. Geometry of the graphic representation should be accurate and characteristics recognisable. For big and middle scales, the first requirement is predominant. Contour lines, for example, ensure geometric accuracy, implicitly including elevations, gradients, stream lines and profiles. Supplementary design techniques allow vivid and plastic terrain representation. Representation of accurate geometry in small scaled maps is not possible and in most cases not necessary. The perception of relief can be increased by the depiction of waters indicating the lowest regions. In the next chapter, contour lines and layers will be discussed in detail, since they support perception of terrain characteristics and will have predominant function in the later proposed design.

Contour Layers

A contour line is an imaginary line on the surface, all points of which are at the same elevation above (or below) some reference datum (often mean sea level) [Met97[63]].

Contour lines may be calculated by graphical or mathematical interpolation or may be measured directly with stereoscopic analysis of aerial views or satellite images. They are artificial lines which only represent topography in cases of rice terraces, coastlines or the edges of the Grand Canyon.

The vertical separation of neighbouring contour lines is called layer or interval. If the layer is constant within one contour line system it is called equidistant. The value of layers depends on the scale, gradient, surface roughness and accuracy of elevation measurements.

Imhof [Imh65[64]] proposes these data for paper maps:

	Map Scale						
α_{max}	2 000	5 000	10 000	25 000	50 000	100 000	200 000
45° (mountains)	2	5	10	20	30	50	100
25° (hills)	1	2	5	10	15	25	50
10° (flat)	0.5	1	2	2.5	5	10	10

Table 2 Equidistant Separation of Contour Layers in meter

Since the maximum gradient changes [a] within maps of small scales it is nearly impossible to realise a uniform layer. Differences in layers increase morphologic characteristics of terrain while legibility and overall impression decreases. The minimal layer is limited by the resolution of the representation media. For paper maps, it is about one third of the value in Table 2.

Generalisation
Defining another separation is the first generalisation to be done. Smaller scales require lower density and that equals higher separation. The easiest generalisation is omitting every second line. In regions with small gradients or relief energy it might be necessary to reduce the line thickness instead of skipping a line. Generalisation further requires that the line shape, be simplified (smoothing) without loosing characteristics or, in

contrast, even emphasising characteristics. In paper based cartography contour lines can be adapted (modified) to rivers or streets and railways if they overlap in small scales. Computer based generalisation is more difficult. Besides former approaches to regularly omit contour lines [Sch84[65]] new methods of adaptive generalisation of relief [Wei91[66]] are being proposed. Weibel generalised the relief characteristics before generating contour lines.

Relief Specific Symbols

Hake [Hak94[67]] proposes several relief specific symbols to increase the vivid representation. Sharp edges, dunes, rock and quarries that represent relief characteristics very well are depicted as discrete symbols in several paper maps.

Shading

The objective of shading terrain is the generation of shadows which emphasise terrain characteristics and make them easy to perceive. A directed ambient light source is placed on the upper left-hand corner of a map, defining the main lighting direction. In handmade paper maps, this direction may be slightly varied depending on the ridgeline orientation of each mountain. However, if the light source is situated at the lower edge representing the lighting situation on the northern hemisphere, topography appears inverted as mentioned before. Shading may be applied – relief energy provided- on scales from 1:25.000 and smaller. Especially at scales near 1:500.000, the combination of contour lines and shading seems to give the best results. The appearance of topography is very vivid and the contrast for the thematic overlay is maximal[Hak94[67]].

Thematic Maps or Charts

Several applications like education, architecture or any kind of navigation require specific thematic maps. As mentioned above thematic maps are usually an overlay onto topographic maps which enables orientation and referencing in case of selectable information. Aeronautical charts as well as nautical charts are navigation charts in the first place. Typical VFR charts are the 1:500.000 aeronautical charts based on the rules of the **I**nternational **C**ivil **A**viation **O**rganisation (ICAO). They are imperative for visual navigation and include topographic objects like towns, roads, waters, forest and relief shading. Flight critical information like airports, radio navigation aids and restricted areas is overlaid. For IFR applications several charts are published like approach charts, obstacle charts and enroute charts.

2.2.2 Scale

On the one hand, the information requirement defines the scale of a maps depending on the amount of necessary symbols. On the other hand, the quantity of necessary maps should reach a minima. Supplementary, precise navigation requires conformal scales.

Conventional paper maps have one fixed scale and the symbology is optimised for this scale. Thus, the scale has a significant influence on map characteristics. Computer based maps have the advantage of no limitations concerning scale. Any scale can be realised depending on user requirements. This enables great degrees of freedom on the one hand, but increased demands on the cartographer on the other hand.

2.3 Implementation into Cavok Flight Guidance Displays

2.3.1 New Concept

There are two ways to maintain terrain characteristics in SVS to support cognitive mapping. First, realism could be increased by showing typical landmarks or satellite images mapped on the terrain. The second alternative is to prepare the terrain data to depict topographic characteristics like ridge and contour lines.

Digital **F**eature **A**lleviation **D**ata (DFAD) consist of culture and cultivation data which can be mapped onto the terrain and maximise realism. The disadvantage of integrating DFAD is that information of direct interest recedes into the background as the total amount of information increases. Additionally, terrain depiction should be independent from the infrastructure. Uncultivated or unexplored environment needs the same density of landmarks as central Europe, for example. Besides these disadvantages from the psychological point of view, there are some technical problems like limited mass data memory, rendering performance and texture memory.

So, terrain depiction should include its real topographical characteristics. In this context, “characteristics” means that the depiction should be detailed and unique. From the technical point of view, detailed depiction requires high resolution of elevation data. In the CFGD terrain is depicted from a DEM as raw data. It is stored in an equidistant lattice of X,Y,Z coordinates with a resolution of 10-30” (300-1000m). DEM with higher resolution up to 1’’ might be available, but mass data memory as well as rendering performance are limiting factors.

The advantages of characteristic terrain depiction are obvious, but its creation seems to be difficult. Since the objective is the enhancement of visual quality, we should search for the solution in human perception and cognition. What are the characteristics of terrain and how can they be extracted from **P**seudo **V**ector **D**ata. Cartographers are very experienced in creating maps, and about 150 years ago, they started shading terrain for a more vivid perception. A very experienced cartographer was Hoelzel who designed hundreds of maps from 1900 till the late 70ies. Of course, none of the maps were based on a **G**eographic **I**nformation **S**ystem (GIS) but on a very good imagination and craftsmanship. Bosse [Bos75[68]] wrote about his work and explained the way in which he designed a new map. First, he tried to see the environment in reality, not just photos or existing maps. Then, he tried to get very precise maps and extracted contour lines, stream lines and peaks. Stream lines are the opposite of ridge lines and are usually identical with rivers. In most cases, he did not have ridge lines, but he generated them from his contour line map. Then, he defined the colour model and started painting for days and weeks, designing maps with an impressive visual quality concerning perception of topography.

The new concept is the emphasis of characteristics from DEM. Information like ridge lines, relative minima and maxima as well as streamlines are implicitly included in the model and only have to be emphasised. The resulting characteristic is no supplemental information cluttering the synthetic depiction. However the topographic depiction has its own characteristic.

Data pre-processing necessary for this data extraction will be called vectorisation in the next chapters. The resulting data generated from the DEM will be called **R**eal **V**ector **D**ata (RVD) since this vectorised information will replace the PVD used by Kaufhold.

2.3.2 Concept Realisation (Environmental Design)

The realisation of the new concept is divided into two major parts. First the process from DEM or raw data to a **D**igital **T**errain **M**odel (DTM) will be described in detail. DTM is a new data model which will serve as the new raw database to which techniques like generalisation, sorting and colour coding will be applied. The result is ready to be visualised and is called **T**errain **D**epiction **M**odel (TDM).

2.3.2.1 Raw data conversion

Vectorisation

Based on the idea of emphasising characteristics we tried to extract characteristics from PVD and created several maps. These maps were then combined into one including all characteristics as vector data. Finally we triangulated terrain for real time rendering gaining RVD. Figure 43 shows this process from DEM to TDM in detail [Bau99[69]].

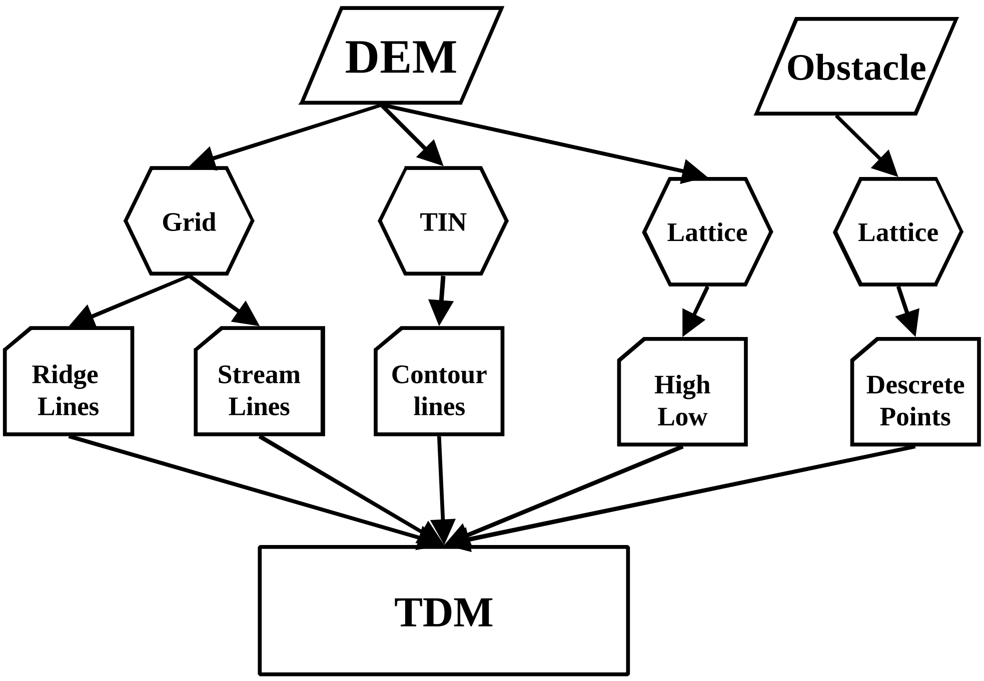


Figure 43 The Process of Vectorisation

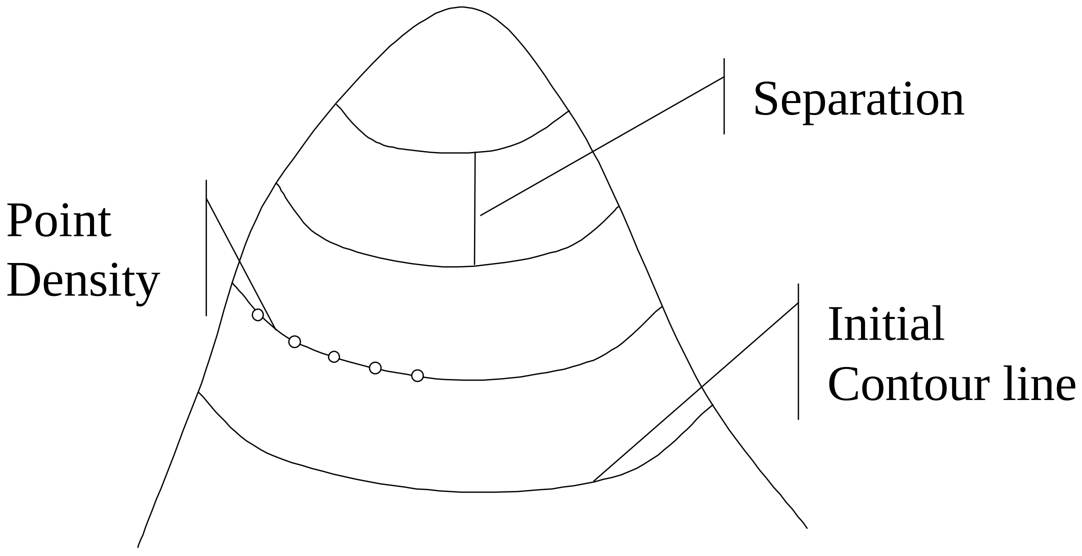


Figure 44 Contour Layer Parameters

The mental process of terrain by analysis (extracting information from an image or reality) is very complex and depends on the individual. Extracting this information technically from a DEM is even more difficult and complex algorithms are necessary. For a first approach, a GIS tool called ArcInfo, that already has certain functionality, was used. Creating contour lines from any data source, whether it be DEM or an irregular set of points, is supported by this tool. The user has the possibility of influencing the process by defining the initial contour line, the separation of contour lines and the density of points describing the contour lines (Figure 44). Another function is the generation of stream lines for a flow model or relative minima, maxima or saddle points.

In a second step, ArcInfo loads all the extracted data sets and creates a TIN. The result is vectorised high quality data ready for Real Vector Depiction. During the vectorisation process the error has to be minimised, too. This can be ensured by a small contour line separation and weed tolerance which defines the point density on one contour line.

The process of vectorisation is visualised in Figure 45 to Figure 49. In Figure 45 and Figure 46, the data input for the vectorisation process (DEM) is shown as wire frame and as shaded terrain respectively. This is state of the art in the CFGD. Extractions of relative maxima as well as of contour lines with an equidistant separation of 150m are shown in Figure 47 and Figure 48. Finally, these vectorised data are re-triangulated. In Figure 49, you can see the result as wire frame depiction, and as in Figure 50 an elevation coded and shaded visualisation.

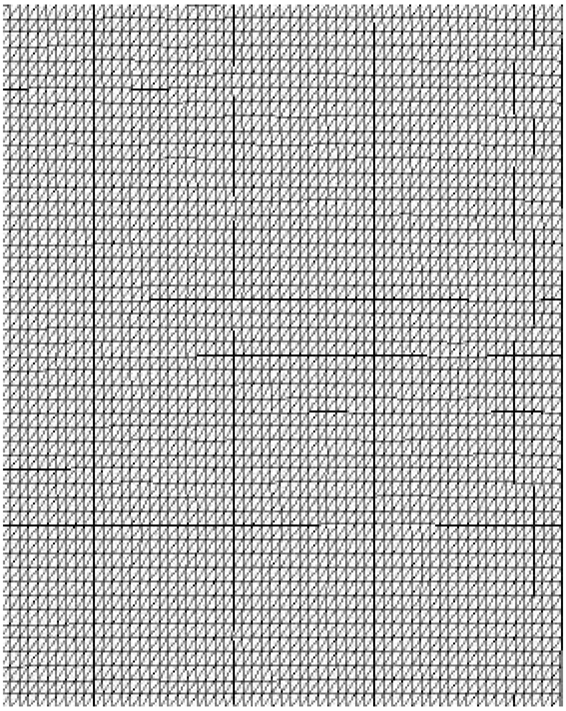


Figure 45 Wire frame Depiction of PVD

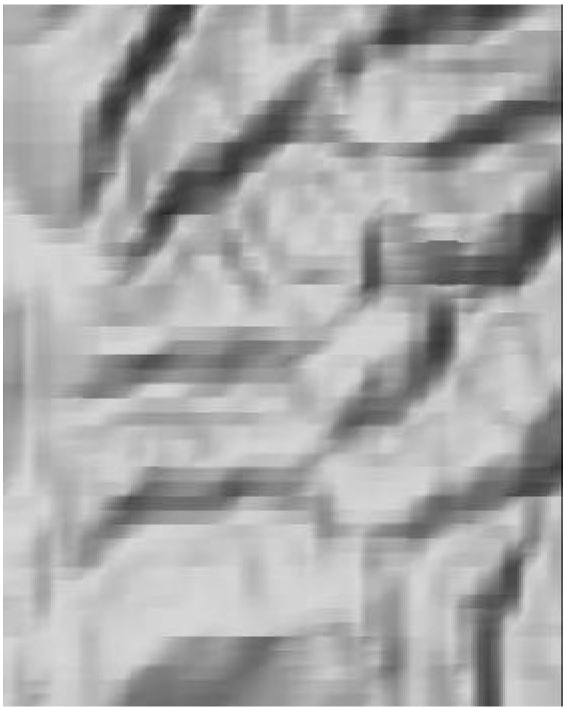


Figure 46 Shaded Surface Depiction of PVD

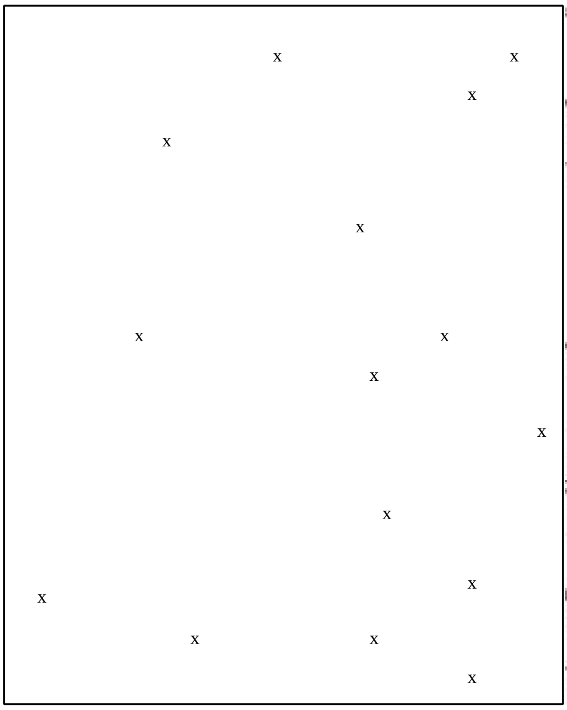


Figure 47 Extraction of Relative Maxima

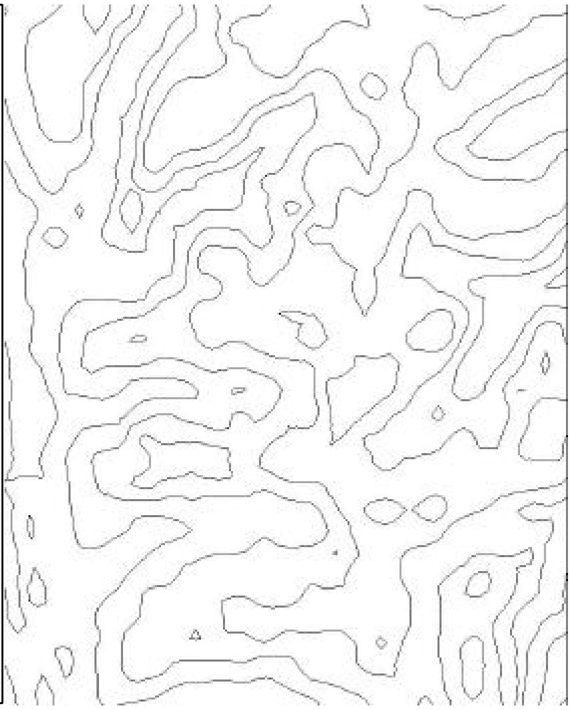


Figure 48 Extraction of Contour Lines

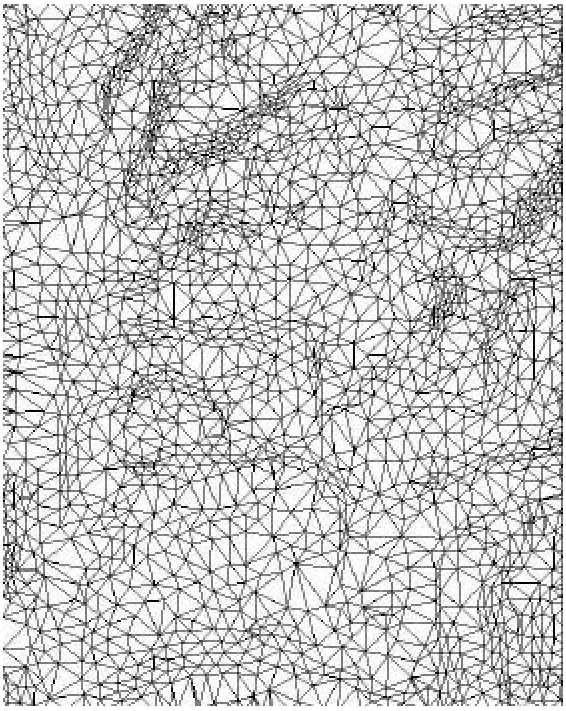


Figure 49 Triangulated RVD

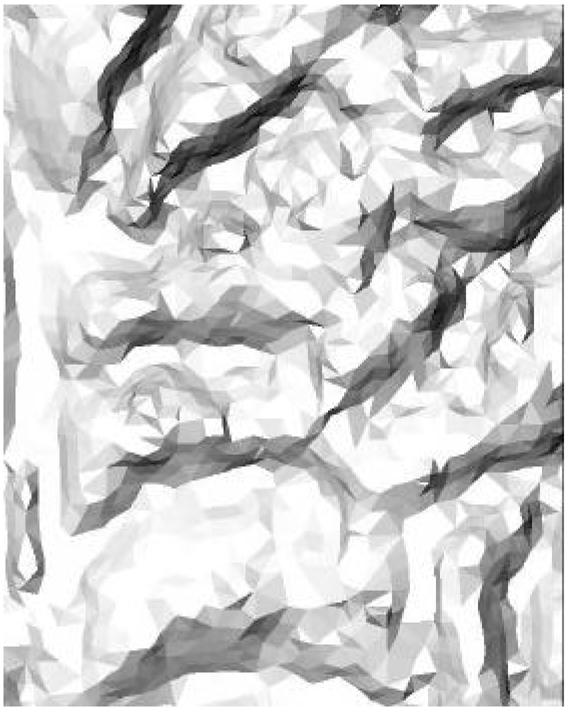


Figure 50 Shaded RVD

As you can see the process of vectorisation already reduces the amount of triangles especially in terrain with low so called relief energy. Relief energy of terrain can be compared to surface roughness of materials. It describes the gradient and amplitude of terrain elevation. Methods of decimating the TDM will be mentioned later.

Triangulation

The aspect ratio defines the ratio of a triangle as the ratio of the longest over the shortest side of the tightest rectangle that encloses the triangle. The tightest rectangle is the rectangle with the smallest area. Long and skinny triangles have poor aspect ratios which are much greater than one while regularly shaped triangles have aspect ratios close to one. Having triangles with aspect ratios close to one is a desirable property, since long and skinny triangles are more prone to rendering and numerical errors. For example, in Figure 51, the long and skinny triangle has a poor aspect ratio while the nearly equilateral triangle has a very good aspect ratio. Note that this thesis does not claim that this is the standard or accepted definition of the aspect ratio of a triangle.

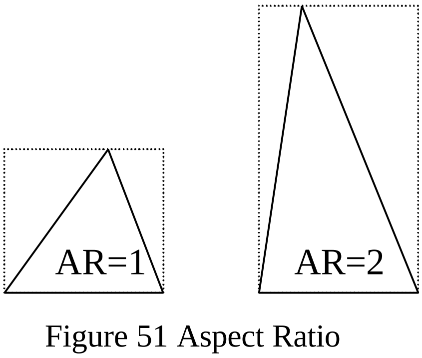


Figure 51 Aspect Ratio

From the rendering point of view, aspect ratios of 1 are best, since the ratio of necessary data and filled surfaces on the presentation media is maximised. So, first during the vectorisation process and then in the triangulation process, parameters have to be carefully selected under this performance aspect.

Normals

Shading of terrain is a very important and highly perfected technique. As already mentioned, a light source at the upper left corner significantly increases the vivid appearance of terrain. From the technical point of view, the angle between lighting vector and object normal is calculated. In the case of small angles, the object colour is darkened simulating shade; in the case of angles close to 180°, the object colour is lightened.

It is necessary to distinguish between two different principles of lighting. The first is based on surface or triangle normals, and the second on point normals. While colour coding fills wire frames and makes the observer perceive objects, surface normals emphasise the edges between triangles. If the normals are not the same there is a discrete step in lighting at these edges. This disturbs the natural impression of object surfaces. The solution for terrain depiction is a calculation of point normals and a gouraud shaded depiction. This is the objective of the database pre-process. Figure 54 shows the same area depicted with surface as well as point normals. Beside Figure 54, Figure 27, Figure 28, Figure 49 and Figure 50 also show the impressive improvement of sharpness of depiction based on the new concept.

Figure 52 Surface Normals

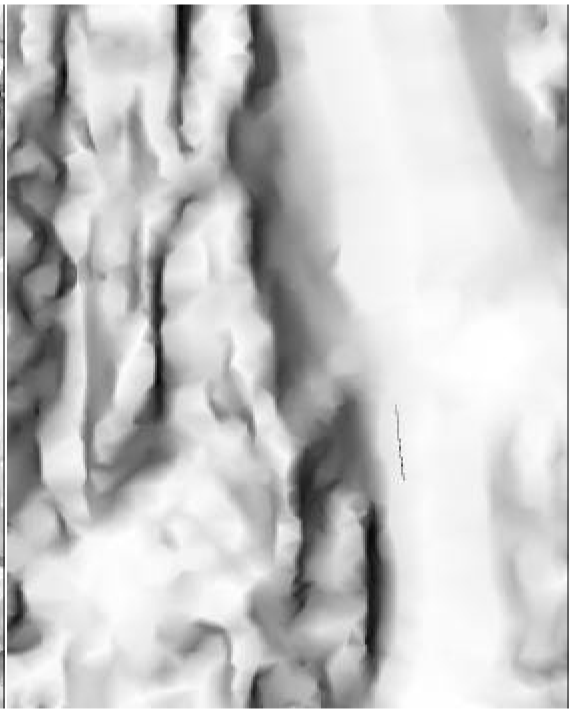


Figure 53 Point Normals

Figure 54 Surface Normals

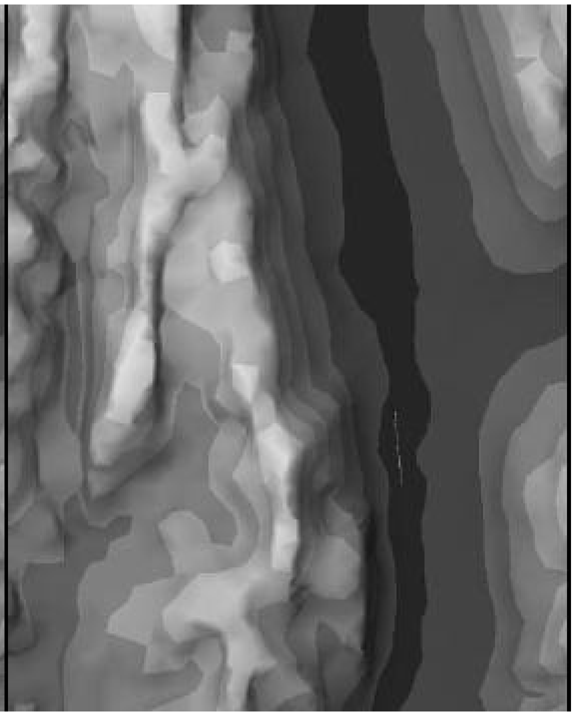


Figure 55 Point Normals

2.3.2.2 Sorting and attribution of the new data model

The DTM is the base for the next process. From the geometrical point of view, these data are ready for population. Points are defined and triangulated. What is missing? Attributes like colour and shading, additional extraction of contour lines and optimisation for the rendering process result in the final TDM. A short excursion to the Inventor format has to be done for the further description of data pre-processing.

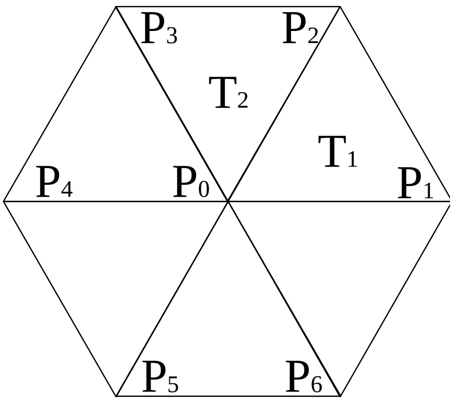


Figure 56 Visualisation of a Hexagon

The Inventor format is a data base format defined and optimised for the storage of visualisation data. Usually an Inventor object consists of two parts. First, a list of coordinates and second, a list of lines and triangles referring to the coordinates. If a hexagon, for example, is rendered, it consists of six separate triangles. Each triangle consists of three points defined in X,Y,Z. So the necessary information for rendering are 54 floats. For the hexagon example, the necessary coordinates are 21 floats and the necessary reference values are 18 integers. Since each triangle neighbours another triangle, the Inventor format enables further optimisation. For so called IndexedTriangleStripSets, the reference list consists only of a list of points that shape the object by triangulating triples of neighbouring points one after another. This technique allows reduction of the necessary data to 21 floats and 8 integers (Figure 56).

$$T_1 \left\{ \begin{array}{lll} X_0 & Y_0 & Z_0 \\ X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \end{array} \right.$$

$$T_2 \left\{ \begin{array}{lll} X_0 & Y_0 & Z_0 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \end{array} \right.$$

.
.
.

$$T_6 \left\{ \begin{array}{lll} X_0 & Y_0 & Z_0 \\ X_6 & Y_6 & Z_6 \\ X_1 & Y_1 & Z_1 \end{array} \right.$$

Conventional object definition

$$\begin{array}{llllllll} P_0 & X_0 & Y_0 & Z_0 & T_1 & P_0 & P_1 & P_2 \\ P_1 & X_1 & Y_1 & Z_1 & T_2 & P_0 & P_2 & P_3 \\ . & & & & & & & \\ . & & & & & & & \\ P_6 & X_6 & Y_6 & Z_6 & T_6 & P_0 & P_6 & P_1 \end{array}$$

IndexedTriangle

$$\begin{array}{llllllll} P_0 & X_0 & Y_0 & Z_0 & T_1 & P_0 & P_1 & P_2 \\ P_1 & X_1 & Y_1 & Z_1 & T_2 & & & P_3 \\ . & & & & & & & \\ . & & & & & & & \\ P_6 & X_6 & Y_6 & Z_6 & T_6 & & & P_1 \end{array}$$

IndexedTriangleStripSet

Perception of Contrast

Perception of contrast has some remarkable effects which can be used for terrain depiction. Before we describe some of the factors which affect human perception of contrast, we need to understand that contrast can be defined in two different ways. One definition is that contrast is the perception of difference in the intensity of areas. This is called perceptual contrast. Contrast can also be defined as the difference in the intensity of two areas. Note that this definition omits the term perception that appears in the first definition. The second definition of contrast is called physical contrast. However, physical and perceptual contrast do not always correspond to one another. One example is the perception of contours[Gol89[70]]. Contour was defined as the “narrow region which visually separates something from something else” [O’B58[71]]. We are particularly interested in contours, not only because they help separate different areas, but also because the sharpness of the contour determines how we perceive the contrast between areas on either side of it. If two areas reflect the same amount of light, but one has a fuzzy contour and the other a sharp contour, the one with the fuzzy contour will contrast less with its background. In fact, if the transition between an area and its background is very fuzzy, the contrast between them can vanish altogether. Stare at the centre of the fuzzy-contoured disc of Figure 57. If you keep your eyes very still for about 30 seconds, the disc will disappear. When this happens, the contrast between the disc and its background has vanished, since we no longer perceive a difference in brightness between the two areas. This is a good example of a situation in which there is physical contrast between two areas but no perceptual contrast. Now see if you can make the sharp-contoured disc of Figure 58 vanish by starring at it in the same way. You will see that this is difficult or impossible to accomplish. The difference lies in the way the two discs stimulate the retinal receptors and in the effect of the jiggle of the eyes.

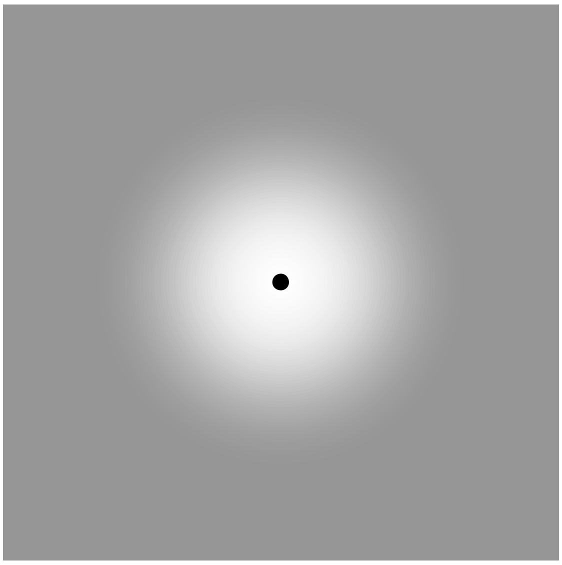


Figure 57 Disc with blurred Contour

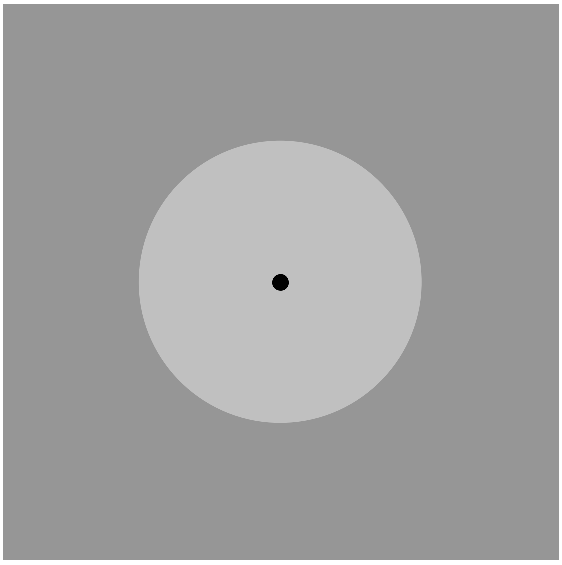


Figure 58 Disc with sharp Contour

Another effect called the Mach bands can even emphasise this perceptual contrast. If you look at Figure 59 you will see areas of different grey scales. If you compare one grey scale to its right and left neighbouring tones, you will recognise that it is darker at the edge next to the lighter neighbour and vice versa.

These effects which are both based on perception will be used for the new terrain depiction. While Kaufhold's terrain was fuzzy and the elevation contrasts vanished, the new terrain depiction has characteristics that serve as sharp lines. Moreover, gouraud shading is replaced by flat shaded contour layers. This technique emphasises contrast perception by the effects of Mach bands.

The objective of vertical sorting is a grouping of triangles within one layer. Grouping allows colour coding of those triangles with one common colour. In Figure 60 and Figure 63 you can see the result of this process.

Figure 59 Mach Bands

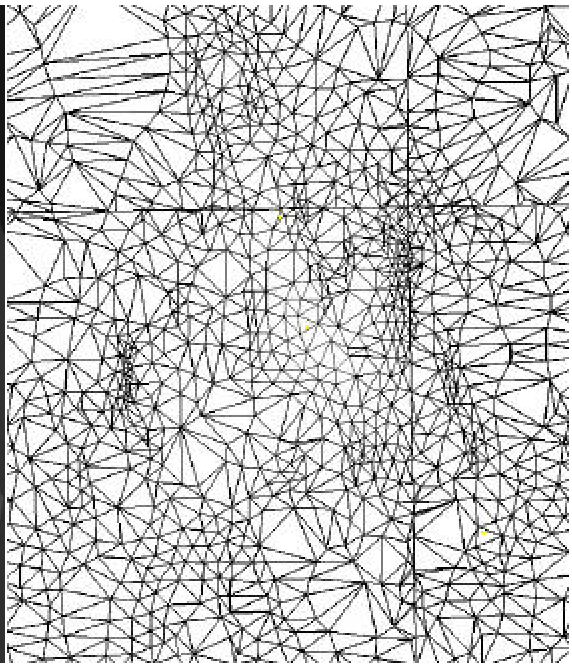


Figure 60 Vectorised and vertically sorted   Figure 61 Wire Frame Depiction

For this reason each triangle is analysed concerning its layer, and the terrain is resorted. After this sorting process, the single object terrain is divided into several objects, each presenting one layer. So, this sorting technique only changes the reference points and not the coordinates themselves. Instead of defining one colour for each point, only a few colours have to be defined for each layer. In Figure 62, the new Inventor structure is sketched. Instead of a material node mapping one RGB value to each point, each layer node has an overall colour definition.

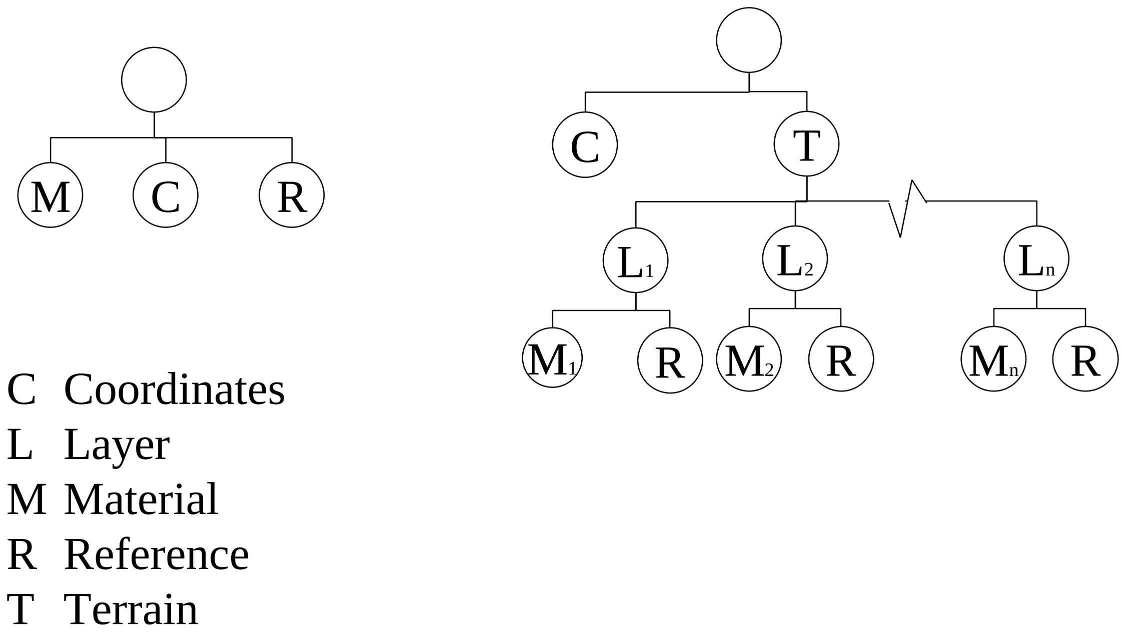


Figure 62 Vertically sorted Inventor Structure

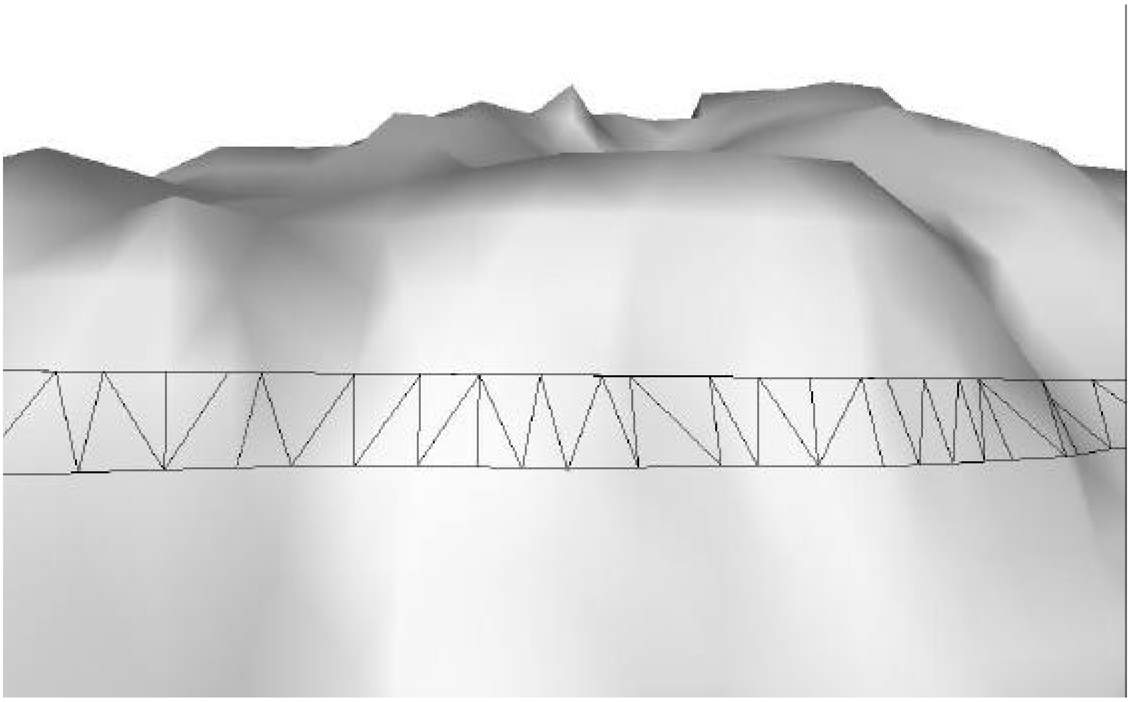


Figure 63 Vertically sorted Triangulated Irregular Network

One positive side effect is a new possibility of hazard avoidance. Since each contour layer has an overall colour definition, this colour value can easily be exchanged online. Depending on the actual altitude, terrain elevation above the aircraft can be coded in any warning colour. This clutters the display, however the warning changes in discrete steps. In the former terrain depiction this terrain warning was very dynamic and dominated the presentation (Figure 64). The choice of colour will be mentioned later.

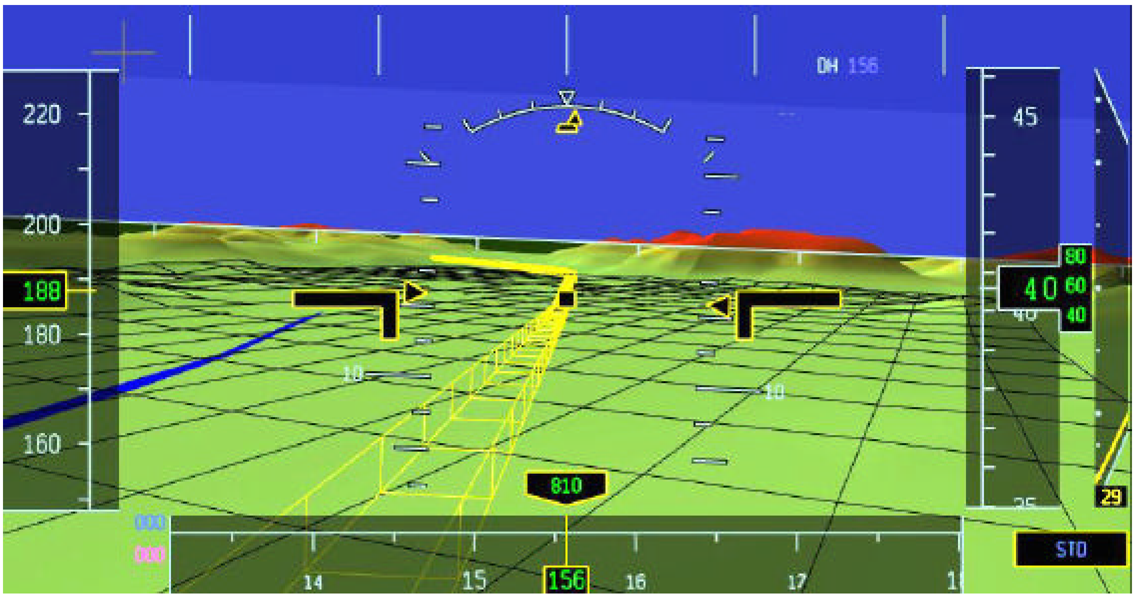


Figure 64 Ground Collision Avoidance with CFGD

Performance Optimisation by Horizontal Sorting

The objective of horizontal sorting is the reduction of necessary rendering performance. However, it is a necessary preparation for the contour line extraction.

The result of the triangulation process leading to the DTM is an unstructured list of triangles. They are neither sorted by elevation nor are the succeeding triangles in the list neighbouring in the depiction. The first deficiency was solved by the vertical sorting process. In the next step called horizontal sorting, the list of triangles within one layer is sorted according to their geometric relation. In the end, two succeeding triangles in the reference list actually neighbour each other in the depiction.

In principle, the DTM is a TIN while PVD are regular. However, PVD are regular only in two dimensions (Latitude and Longitude). This sorted DTM is regular in elevation. For this reason, I introduce the designation **T**riangulated **S**emi **I**rregular **N**etwork (TSIN). You can see the importance of the difference looking at the necessary rendering performance: from regular data the graphic engine can render meshes with the mentioned advantages, while a TIN cannot be rendered as one mesh. TSIN can be rendered as a mesh because of its regularity in elevation. Each contour line is one mesh reducing necessary transformations in the geometry engine to about 35% of the number usually required.

Contour line extraction

The effect of sharp contours and Mach Bands increases the perceptual contrast while the physical contrast is constant. The use of this effect is very important, since the available grey scale is very limited and only covers an elevation range of about 9000m. There is another possibility for increasing the perceptual contrast. The effect is the same as sharpening the contours. Figure 65 shows the shape of France.

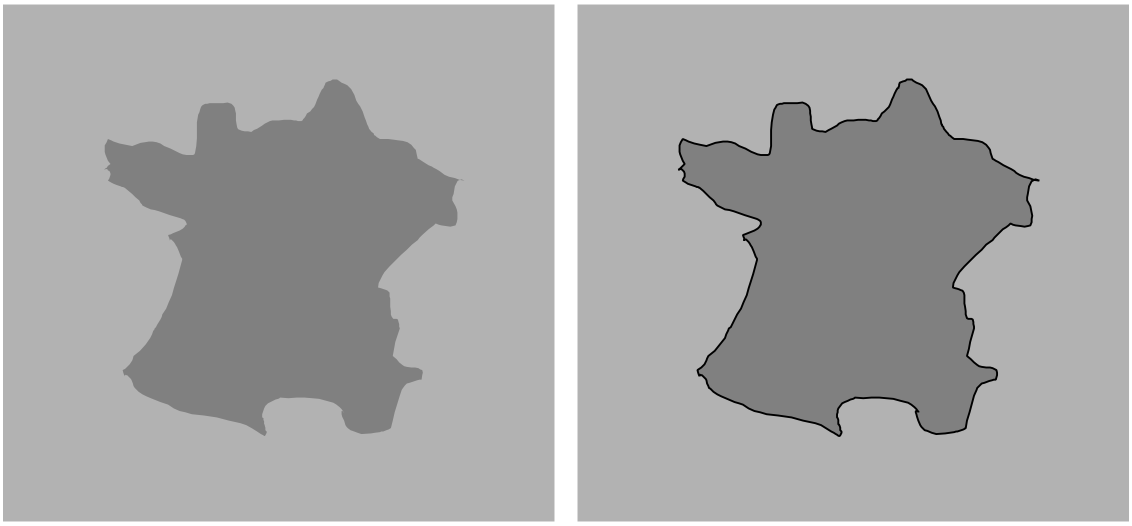
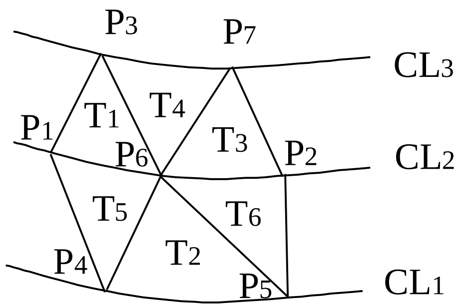


Figure 65 Increase of Perceptual Contrast



Vertical Sorting:	L_1:	$\{T_1, T_3, T_4\}$
	L_2:	$\{T_2, T_5, T_6\}$
Horizontal Sorting:	L_1:	$\{T_1, T_4, T_3\}$
	L_2:	$\{T_5, T_2, T_6\}$
Contour Lines:	CL_1:	$\{P_4, P_5\}$
	CL_2:	$\{P_1, P_6, P_2\}$
	CL_2:	$\{P_3, P_7\}$

Figure 66 Data Pre-Processing

Figure ground segregation is enhanced by a thin black line. As you will notice, the perceptual contrast is not constant, while the physical one is. If you compare the first and the last picture, the shape appears much darker if the contour line is present. Besides the increase of perceptual contrast, the enhanced figure ground segregation supports the perception of a figure or shape. This effect can also be used for terrain depiction.

Since triangles are sorted vertically as well as horizontally, it is easy to extract contour lines from the existing data. Neighbouring points are connected via triangles which enables creation of line sets[Web00[72]]. A summary of the sorting processes is visualised in Figure 66. The terrain depictions of Figure 67 and Figure 68 are an example of the contrast between the old and the new terrain depiction. The choice of grey scale is identical, so the physical contrast is the same. However, the perceptual contrast is impressive.

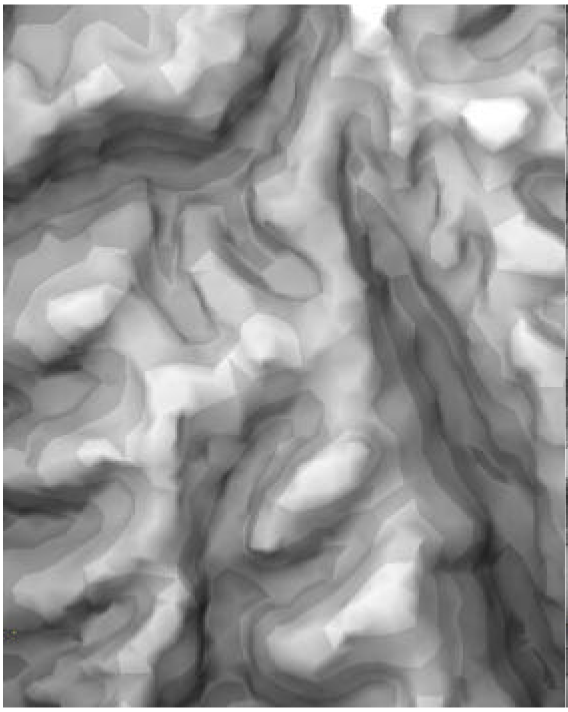


Figure 67 Greyscale Contour Layers

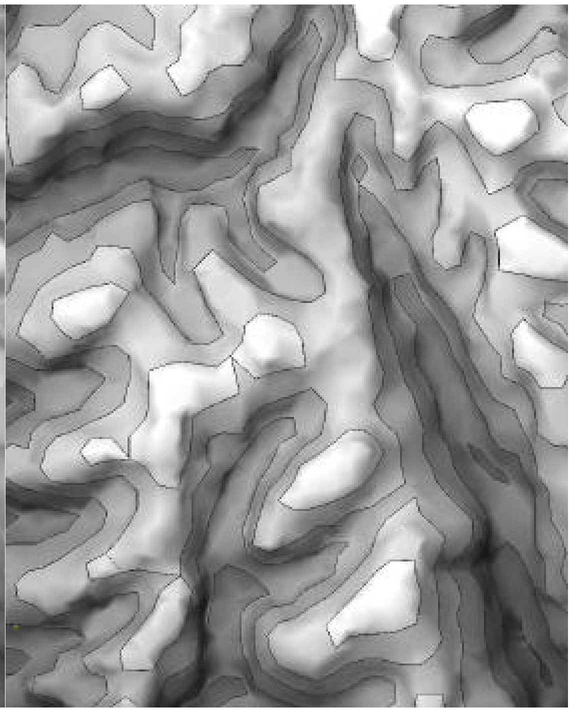


Figure 68 Increase of Perceptual Contrast

Colour Models

In cartography, elevation on topographic maps is usually colour coded. Different coding techniques like “the higher the lighter” from grey green to white or “the higher the darker” from white to brown have been explored in the last century. Today conventional colour scales are:

0 - 100 m	Blue-green
100 - 200 m	Yellow-green
200 - 500 m	Yellow
500 -1000 m	Light-brown
1000 –2000 m	Brown
2000 –4000 m	Red-brown
Above 4000 m	Brown-red

This colour model has been used by Baumgart [Bau99]. He used 150m contour separation and defined a colour table that had a specific quality. He selected three colours which are mentally grouped to one tone. This choice makes terrain close to the viewer’s position look separated into 150m steps, while more distant terrain seems to be separated into 450 m steps. Natural decluttering caused by this colour table works very well. However, a more significant decluttering is desirable. Kaufhold proposed a grey colour table for a strong segregation of overlay symbology from the terrain information in background. Especially the red warning for collision avoidance is more attractive. But conventional grey scaled terrain has a significant disadvantage. Since elevation as well as shading are only based on grey, it is impossible to distinguish between low but lighted or high but unlighted terrain. So the conventional terrain is ambiguous if it is grey scaled. In contrast to this, the TDM strongly supports grey scales, but since each layer has one common grey scale, if the TDM is lighted homogeneously, the aforementioned problem is non-existent.

Generalisation / Level of Detail

A **L**evel **o**f **D**etail (LOD) is a single representation of a model. A greatly simplified model is a low level of detail. A marginally simplified model is a high level of detail. The original model is the highest level of detail. The levels of detail of a model are the model and all its simplified versions grouped together. When rendering an object, a graphics system substitutes different levels of detail for the original model according to how far away the viewer is. As mentioned above, conventional polygonal decimation techniques result in distorted depiction. Weber [Web00] realised a polygonal simplification based on two concepts. First, he omitted one contour line and re-triangulated the remaining points. Second, he omitted one contour line as well as several points on the remaining line. These techniques assure that the loss of characteristics is minimised.

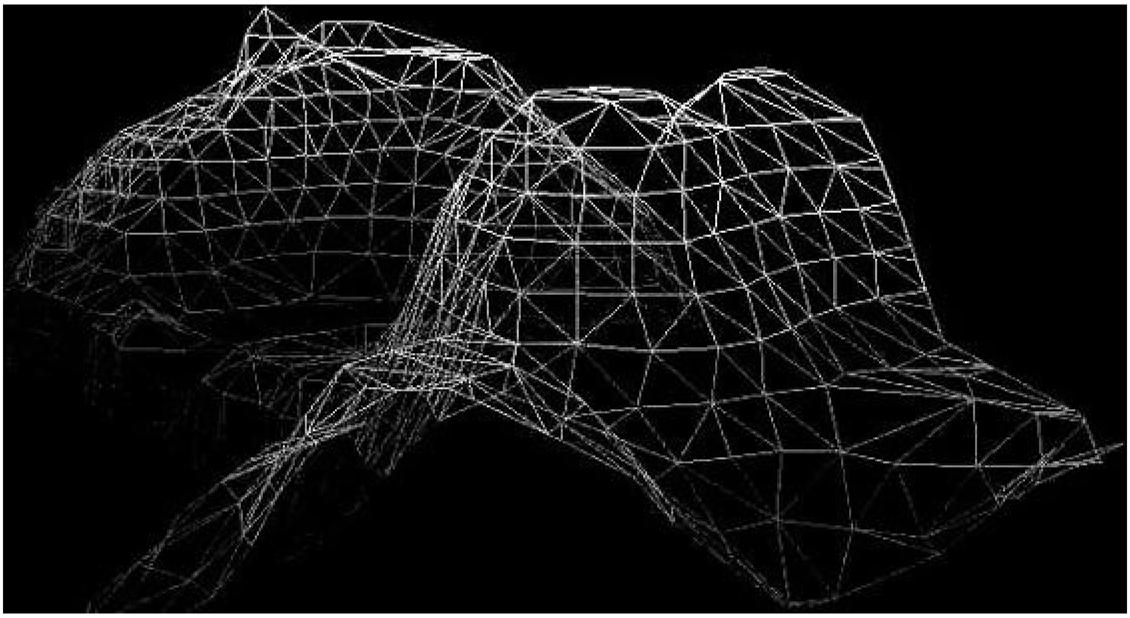


Figure 69 Highest Level of Detail

Figure 69 shows the highest level of detail of a generated tile. Figure 70 shows the same tile with no supplement data but re-triangulated with a different contour line separation. Here you can see as well as in the example Figure 71 to Figure 73 that terrain characteristic is maintained even if the amount of triangles is decreased significantly. This technique can be applied on terrain that is far from the viewers position and for low zoom levels. The use of level of details allows thus to increase the range presentable on the navigation display which will support survey mapping.

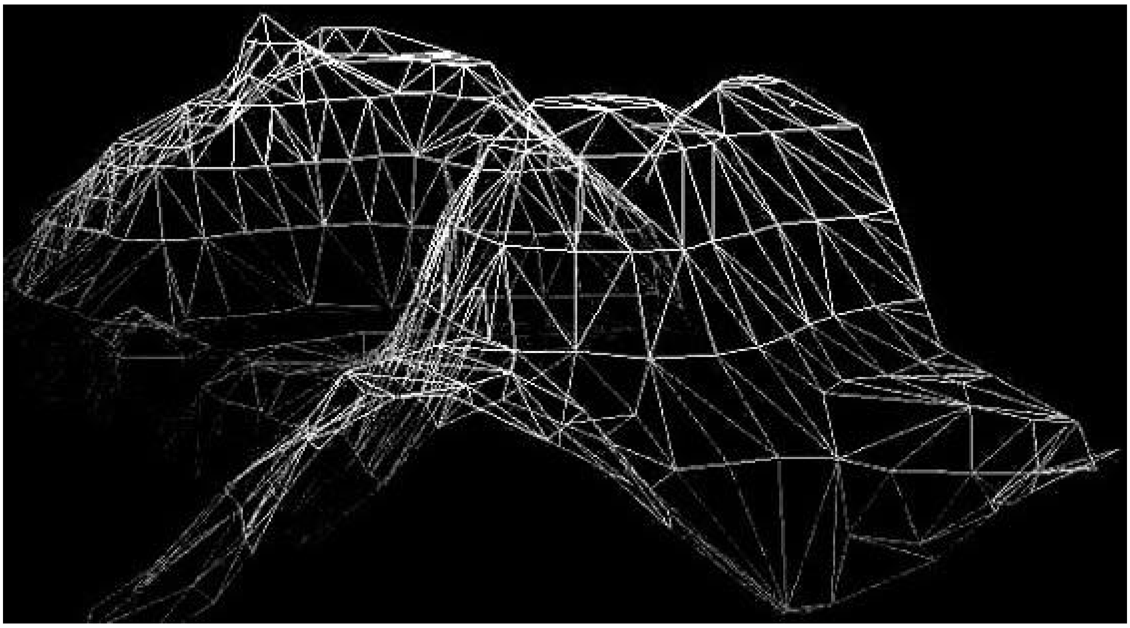


Figure 70 Low Level of Detail

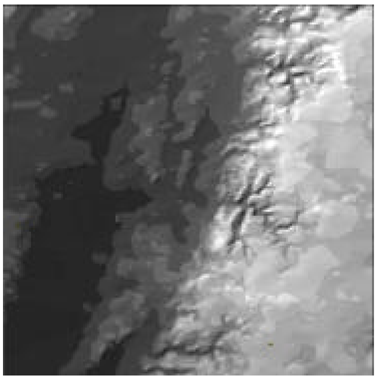


Figure 71 Layer: 50m

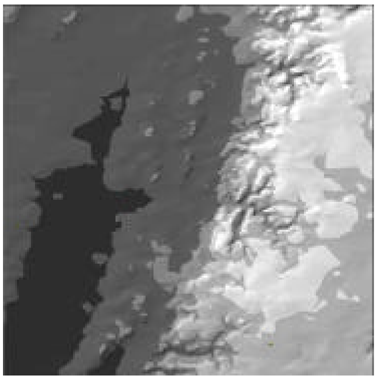


Figure 72 Layer: 100m

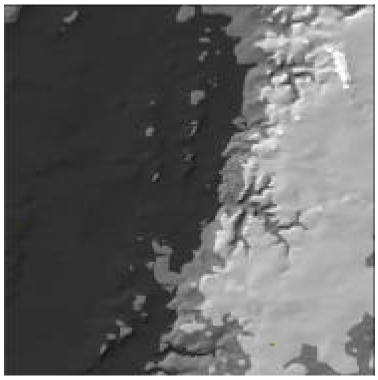


Figure 73 Layer: 150m

2.3.3 Improvements for Perception and Cognition

This chapter is a short summary giving a better overview of the new concept, results and advantages. Psychological advantages have to be evaluated in experiments. They will be mentioned here from the author's point of view and serve as a hypothesis for the next chapter as far as it is necessary to evaluate them. Technical advantages, on the other hand, are objective and will be discussed here. Figure 76 and Figure 77 show the four major steps in terrain pre-processing. The basis for this thesis was PVD as they were used by Kaufhold. Disadvantages were analysed, and they motivated further development. The main process is the vectorisation of terrain characteristics and creation of the DTM. This intermediate result was used before to emphasise the blur of the former depiction. Based on this new model the terrain depiction was first enhanced by contour layers and then by supplementary contour lines.

Results have only been presented as snapshots of small areas. Before discussing the results, an example for the application in the Cavok FGD will be given.

2.3.3.1 Psychological Improvements

As already mentioned, the psychological aspect is subjective and has to be evaluated in specific experiments. Some effects like the increase of perceptual contrast or the reduction of blur may be noticed and will not be an issue for further experiments.

2.3.3.1.1 Perceptive Improvements

No Blur Effects

Blur arose from raster data on the one hand, and gouraud shading effects on the other hand. The new vectorised TDM solves this problem since triangle edges are the edges of colour steps as well. Figure 79 shows the example we know from the problem analysis. With flat shading as well as gouraud shading techniques, it was impossible to depict a smooth isohypse. Since elevation was colour coded, the tone should have changed exactly at this line. Gouraud shading as well as flat shading may be depicted now without any blur.

Figure 74 Kaufhold's PVD

Figure 75 Linear TDM

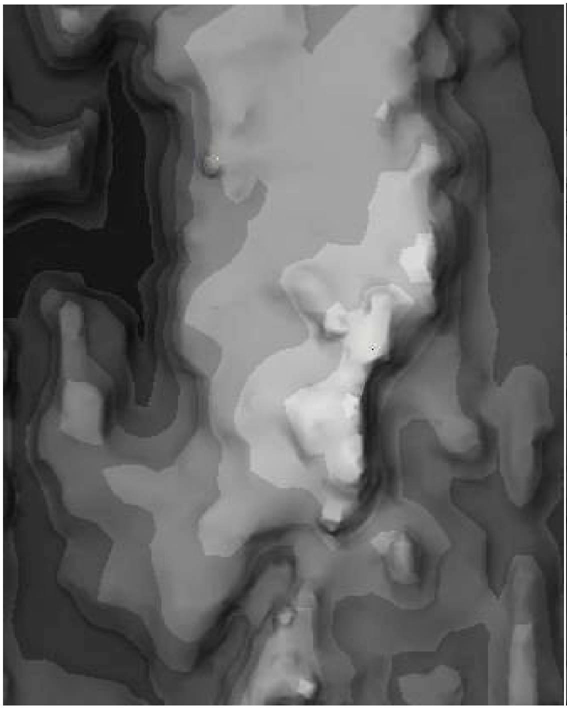


Figure 76 Layered TDM

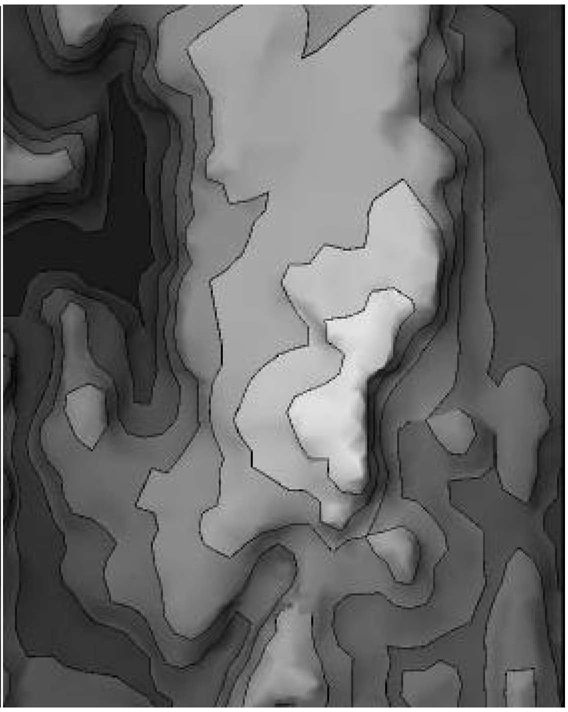
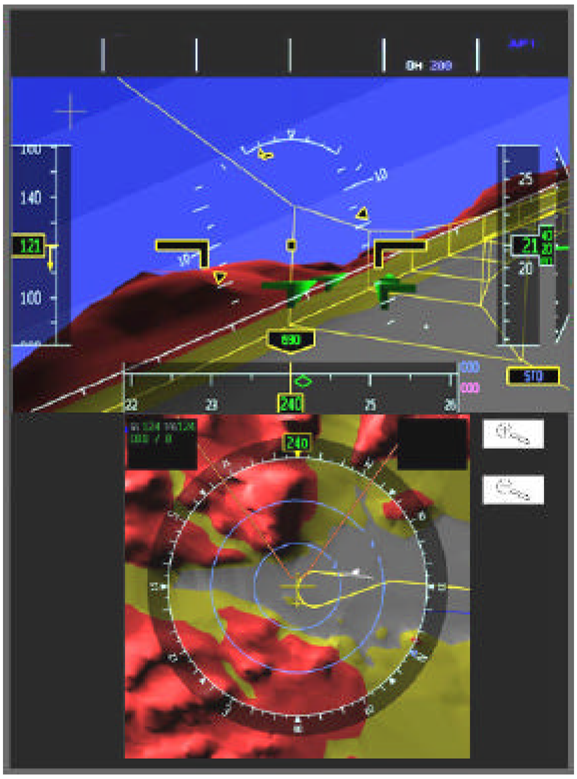


Figure 77 Layered & lined TDM



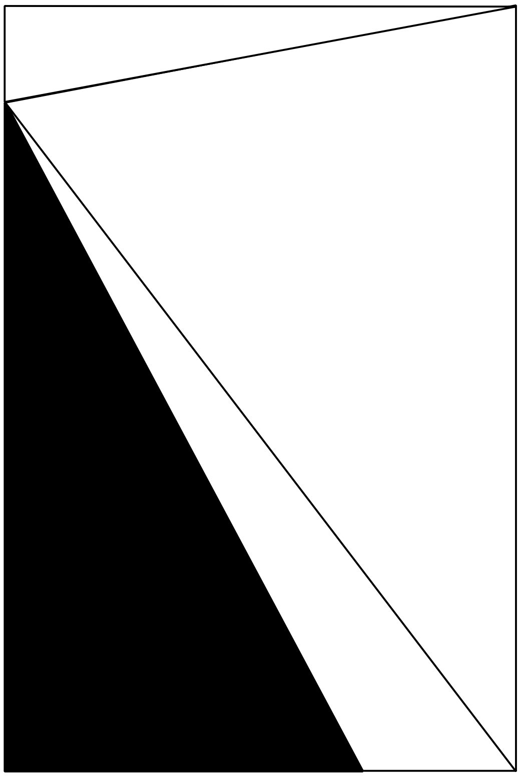


Figure 78 Approach to Salzburg Airport

Figure 79 Triangulated Isohypse

High Zoom Robustness

The new vectorised TDM depicts terrain characteristics as real vector objects. It may be compared to vector graphics as we know them from CorelDraw, for example. Any zoom level is feasible and diagonal lines for example will always look sharp. Of course the amount of objects will decrease within one window, but the object will behave as expected and not be disturbed by steps or big pixels. In Figure 80 and Figure 81 both depictions are shown at different zoom levels. The upper image depicts about 100x100 km², the second 30x30 km² and the lowest about 10x10 km².

Figure 80 Kaufholds PVD

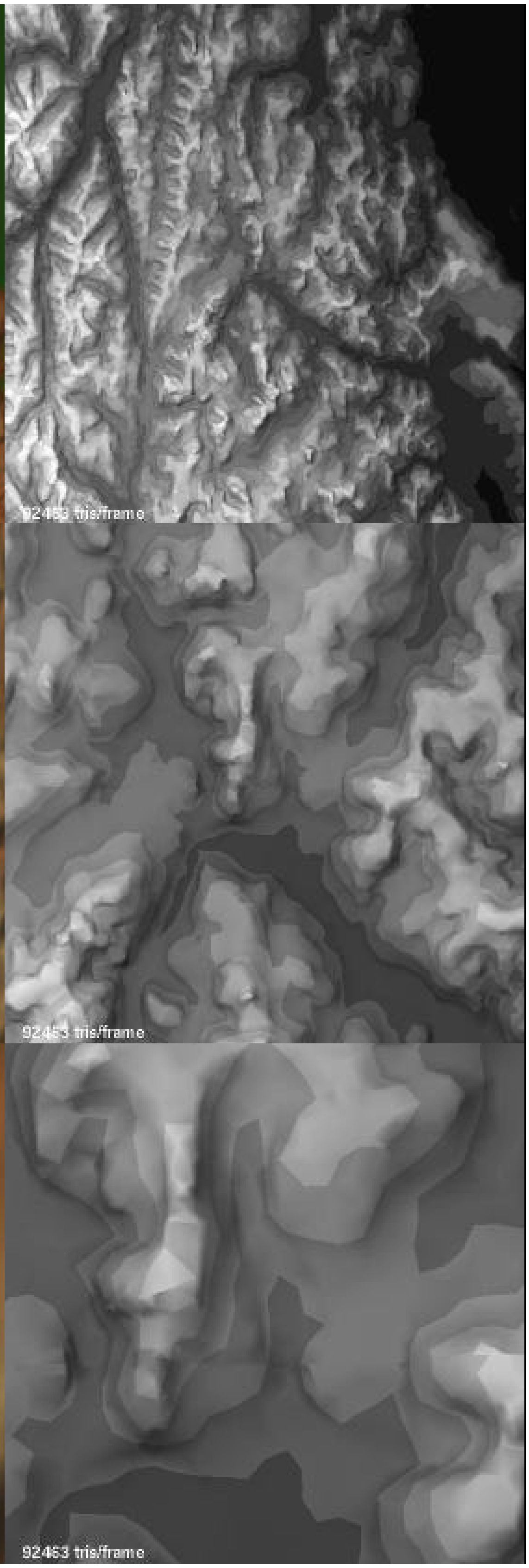


Figure 81 Contoured RVD

Amplification of Characteristics

Compared to any other decimation algorithm, the proposed decimation is much better with regard to maintenance of characteristics. Instead of decimation, the expression generalisation should be used. While decimation usually decreases the visual quality, generalisation in cartography can enhance the perception of characteristics it.

Improved Depth Perception

Perceptive advantages mentioned above mainly refer to the depiction on the navigation display. However, there are major advantages of the new TDM concerning the PFD as well. The perception of depth especially on this display is very important for distance and dimension estimation. Kaufhold used a regular grid on the ground for linear perspective. This depth cue is common and very strong. We know it from converging roads or railway tracks.

Pairs of contour lines achieve the same impression. The terrain depiction on the PFD looks like Grand Canyon (Figure 82) or the Monument Valley. Natural contour lines in this kind of landscape significantly support perception of dimension.

Enhanced Elevation Estimations

Besides the improvement of linear perspective this terrain depiction allows estimation of the actual altitude in reference to any mountain. The contour line of the altitude itself is a horizontal line in any direction to the present position. This effect makes it easy to decide if the estimated flight path is clear of terrain or obstacles.

Since contour lines are equidistant it is possible to estimate altitudes and differences in altitude very well. This estimation can be objectified by counting contour layers. Finally, the comparison of neighbouring peaks or ridge lines is very easy using contour lines instead of the conventional terrain depiction.

Figure 82 Grand Canyon

Contour Lines support Grey Scales

The ability to depict terrain without colour is a major advantage of the new depiction. Baumgart found in his presentation of the curved approach to Salzburg that decluttering works excellently. The yellow “tunnel in the sky” as well as the 2D symbology is segregated from the terrain as you can see in Figure 78.

Contour Lines support Pattern Recognition

Changing characteristics depending on the lighting situation was a main problem of the conventional terrain depiction. The display static light source modified or distorted the topographic characteristics and made it difficult or impossible to recognise areas. As mentioned above, the only terrain specific depiction was the elevation coding. However, the shading dominated and suppressed these characteristics.

The new TDM has very strong characteristics. Contour layers are perceived as patterns and are supported by the distinct contour lines improving the perceptual contrast. Unlike the old depiction, extreme characteristic pattern is not disturbed by the shading. Here the pattern or topographic characteristics dominate the shading.

Since this advantage is the basis for the detection of landmarks, it will be evaluated in experiments.

2.3.3.1.2 Cognitive Improvements

Detection of Landmarks is enabled

Landmarks are elements on the lowest level of cognitive mapping. Any kind of characteristic, specific or unique object can serve as a landmark as long as it can be identified unambiguously. What we found from introspection is that contour layer patterns are very suitable for recognition and cognitive mapping. Every contour layer is unique and has a characteristic shape. Interrelations between contour layers, like proximity or common shapes, are very easy to recognise. Since the human mind is very good at pattern recognition and mental rotation, it is very easy to solve spatial problems in this new environment.

Creation of a Cognitive Map is significantly supported

As mentioned above the psychological advantages are subjective and, at this point, based on the introspection of the author and his colleagues. Thus, especially this main advantage of improved cognitive mapping which was the objective of this thesis has to be evaluated in experiments. The experiments and results will be described in the next chapter, however, a first result will be given here.

Darken or other researchers proved in experiments in virtual environments that cognitive mapping based on synthetic vision is very difficult. Especially the deficiencies of the terrain depiction concerning cognitive mapping prevented the detection of landmarks. There were two solutions: increase of reality by the use of satellite textures and increase of reality by the use of special features like tourist landmarks. The golden mean between the necessity of landmarks and the necessity of abstract, decluttered depiction for flight guidance application had to be found. From the author's point of view the depiction of grey scaled contour layers and contour lines is sufficient for cognitive mapping for large scale environments. The obtained characteristics work at different zoom levels as well as any lighting situation. Problems like flying to a destination multiple times in the flight simulator and always feeling unfamiliar do not exist anymore. However, extensive experiments and their results will be given in chapter 3 and should be continued in further research projects.

2.3.3.2 Technical Improvements

Technical improvements are classified into two groups. First, mass data reduction decreases the necessary size of onboard storage devices, bus sizes and transfer rates. Second, the reduction of necessary rendering performance increases the update rates with the same hardware performance, or the necessary hardware performance can be reduced as well.

Mass Data Reduction

One major advantage of the layer concept is the joint colour definition for all triangles of one layer. In Figure 56, the example of a hexagon was given. Each point of this hexagon consists of the three coordinates and three colour values RGB. Since all triangles of one layer have the same colour in the layer depiction the individual colour values can be replaced by a minimum of joint values. This method allows the reduction of the mass data by 25%, which is a significant improvement.

The major improvement, however, is the data reduction realised by the vectorisation process. Since the reduction strongly depends on the resolution of the input data, decimation rates should be referred to visual quality. If you look back at Figure 80 and Figure 81, you will see the difference in visual quality. The value in the lower left corner indicates the rendered triangles per frame. While the contour depiction is rendered from about 90.000 triangles, the conventional depiction which looks very blurred is rendered from 30% more triangles.

This indicates that the vectorisation process allows simplification of the terrain model and an increase in visual quality at the same time.

$$
\begin{array}{ll|l}
T_1 & \left\{ \begin{array}{lll} X_0 & Y_0 & Z_0 \\ X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \end{array} \right. & \begin{array}{lll} R_0 & G_0 & B_0 \\ R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \end{array} \\
T_2 & \left\{ \begin{array}{lll} X_0 & Y_0 & Z_0 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \end{array} \right. & \begin{array}{lll} R_0 & G_0 & B_0 \\ R_2 & G_2 & B_2 \\ R_3 & G_3 & B_3 \end{array} \\
 & \{ & \\
T_6 & \left\{ \begin{array}{lll} X_0 & Y_0 & Z_0 \\ X_6 & Y_6 & Z_6 \\ X_1 & Y_1 & Z_1 \end{array} \right. & \begin{array}{lll} R_0 & G_0 & B_0 \\ R_6 & G_6 & B_6 \\ R_1 & G_1 & B_1 \end{array}
\end{array}
$$

unnecessary

Reduction of necessary Rendering Performance

The reduction of triangles does not only affect the reduction of mass data but also the necessary rendering performance. The correlation is linear, which means the necessary hardware performance for the conventional depiction is also 30% higher.

Another advantage of the contour depiction is the overall colouring within one layer. Instead of performance intensive gouraud shading, flat shading is sufficient and even increases the visual quality.

Compatibility with existing data formats

As described above, the new terrain depiction model completely replaces the conventional equidistant raster model. However, if it is necessary for any reason, an integration of the raw data into the new model is possible. If you look at Figure 83 for example, you will see the environment of Salzburg airport from the North. For this example, the former regular grid was maintained and could be used as a grid texture for the proximity of the runways. You can recognise how impressive the data reduction is for the Salzach valley. This opportunity makes the terrain model compatible with any further requirements.

2.3.4 Summary

Based on the hypothesis that cognitive mapping is possible in a synthetic spatial environment, a new method of terrain presentation was developed. The objective to design a terrain presentation adapted to human requirements concerning perception and cognition was reached by the modification of digital terrain models.

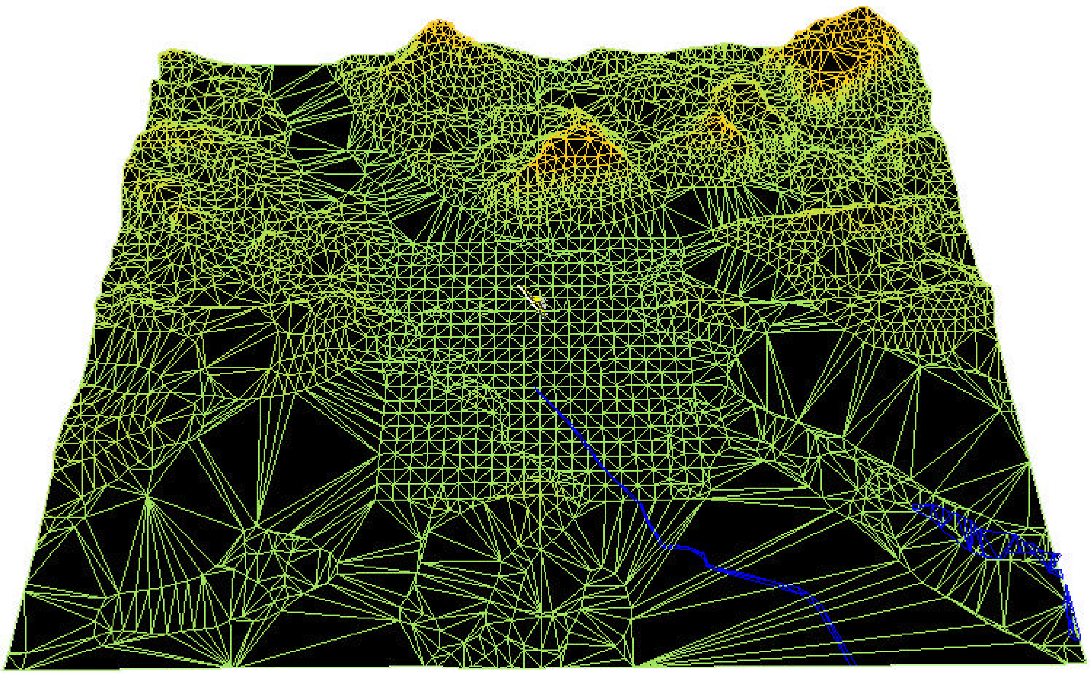


Figure 83 Wire frame depiction of the environment of Salzburg Airport

The process of contour layer generation was explained, and advantages to perception were described in detail. Concerning perceptual improvements, the significant reduction of blur effects, a high zoom robustness, the amplification of characteristics, the improvement of elevation estimations, the reduction of necessary colours and the support of pattern recognition have to be mentioned.

Cognitive improvements have to be evaluated in experiments. However, the detection of landmarks is enabled by the perception of characteristic patterns. These landmarks were the prerequisite for a cognitive map.

A new concept of terrain depiction was presented and realised for a representative environment of 60.000 km². Within this environment all typical terrain, like lowlands, highlands and high mountain regions, was processed. The process from DTED raw data to the terrain depiction model is fully automatic and available for further terrain processing.

3 Evaluation

Attempts will be made to provide behavioural evidence of the advantage of contour emphasis over the raw pictorial information that is provided by the present system. While Figure 76 was used to suggest the increased distinguishability of contrast enhancement, formal experimental results are still needed to help substantiate that impression in the context of a typical pattern recognition task. Such results may also serve to generalise the cognitive advantage of the enhanced contour line depiction to different samples of landscape display.

The main hypothesis relies on the known fact that contour lines serve to identify objects by their shape [Hoc97[73]]. The perception, processing and retention of a depiction providing object-like detail should be better than those of conventional modes of presentation. Ultimately, the more structured material is expected to support the acquisition of relatively stable spatial information which is a prerequisite for the acquisition of a true cognitive map from the synthetic environment.

In a first line of experimentation, the subjects will be requested to sequentially match two views of a circular sample of synthetic landscape which are presented on a computer screen. Variation of the rotation angle renders the design as a variant of Shepard and Cooper's [She82[74]] pattern recognition task. Further on, these short term experiments have to be extended for a final validation of the Cavok flight guidance displays.

3.1 Pattern Recognition Task

Landmark recognition requires unique and distinct objects or areas within a topographic environment. Characteristic patterns are sufficient for landmark recognition, but they were not provided by the conventional terrain depiction. In this line of experimentation, the improvement of simple pattern recognition will be evaluated.

3.1.1 Theoretical Base

Shepard and his team designed several pattern recognition tasks and did research on human behaviour. He focused his work on mental rotation of different two and three dimensional objects. One important result was the similarity of physical and mental rotation. The material he presented to subjects was random shapes. First, subjects were familiarised with a set of these shapes and the reflected versions. During the experiment, these shapes were shown rotated in steps of 60°. Cooper measured the necessary time for recognition and evaluated a linear correlation between rotation angle and recognition time [Coo75[75]]. The average rate of mental rotation was 460°/s, for example. This kind of experiment was used to quantify the advantage of the contour layered terrain depiction.

3.1.2 Method

The experiment had three randomised independent variables: rotation angle, zoom factor and type of terrain depiction. Standard and reflected versions served as control variables. Each set consisted of two stimuli. While the left image served as the original, the right one was rotated in relation to the left by 90°, 180° or 270°. In 50% of these sets the right stimuli was a reflected or “mirror-image” version of the left one. The subject’s task was to decide whether the right stimuli showed the standard or reflected version. Dependent variables were response time measured in milliseconds and the number of correct answers, further on called hits.

Subjects

34 subjects participated in this experiment. As mentioned later, two subjects had to be taken out of consideration. Eight of the remaining 32 subjects were female and 24 male. Sixteen were between 15 and 19 years old, twelve between 20 and 24 and four between 25 and 29. Twenty-seven were students and five were Ph.D. students at Darmstadt University of Technology. Since pattern recognition is a basic skill from a certain age on, it is expected that results are similar for other populations. On the other hand experts are not available since the Cavok displays are not realised today.

Stimuli

Two types of stimuli were selected for use in quantifying the improvements of pattern recognition by the depiction of contour layers. For this reason, the subjects were split into two groups of 16. Since the positive influence of contour layers on pattern recognition tasks was to be evaluated, the vectorised terrain with a linear colour model was compared to the contour layered one. This choice guaranteed that the measured improvement was caused by the different way of depiction and not by the vectorisation of the terrain model. In chapter 5 Figure 75 and 76 (overview of development), the two pictures in the middle are examples for the selected stimuli. The colour table was selected to range from dark brown at low elevations to light brown at high elevations. For the first set of stimuli, a homogeneous change of colour was realised which will be called “linear terrain”. In contrast to this conventional depiction, contour layers were depicted in the second set of stimuli which will be referred to as “layered terrain”. As mentioned above, the terrain data were identical. The vertical separation of contour layers was equidistant for all altitudes with a value of 150m.

Material

For this experiment a terrain model for the region of the Alps was processed. It covered an area of about 50.000 km² from 11°E 46°N to 13°E 48°N. From this area 12 more or less characteristic points were chosen. Snapshots of a vertical projection of these points were taken at 3 different zoom levels. Zoom I covered an area of 16 km², Zoom II 64 km² and Zoom III 144 km². These stimuli were rotated in the picture plane and their order in the experiment was randomised. Pictures No. 10,11,12 were only used for the test trial.

Each subject of one group had the same 180 sets of stimuli in the same randomised order. The difference between the two samples was the linear and the layered depiction as mentioned above.

Two circular fields of the same location and zoom with black surroundings were presented side by side. The diameter of each stimuli was 15 cm, the distance between was 6 mm.

Hard and Software

The experiment was realised on a Personal Computer based on Visual Basic. A 17” colour monitor with a frame rate of 50 Hz served as presentation device (Nytech NM17T57AL). The resolution was 1024 by 768 pixels with a 32 bit true colour depiction. The background of the stimuli was grey. Figure 84 shows a screenshot.

This monitor was placed in a room with several computer terminals. In front of the monitor was a chair with vertical adjustment and rolls which allowed subjects to position themselves at a distance of 60 cm from the monitor. Disturbing reflections were suppressed by a black curtain surrounding the experimental arrangement.

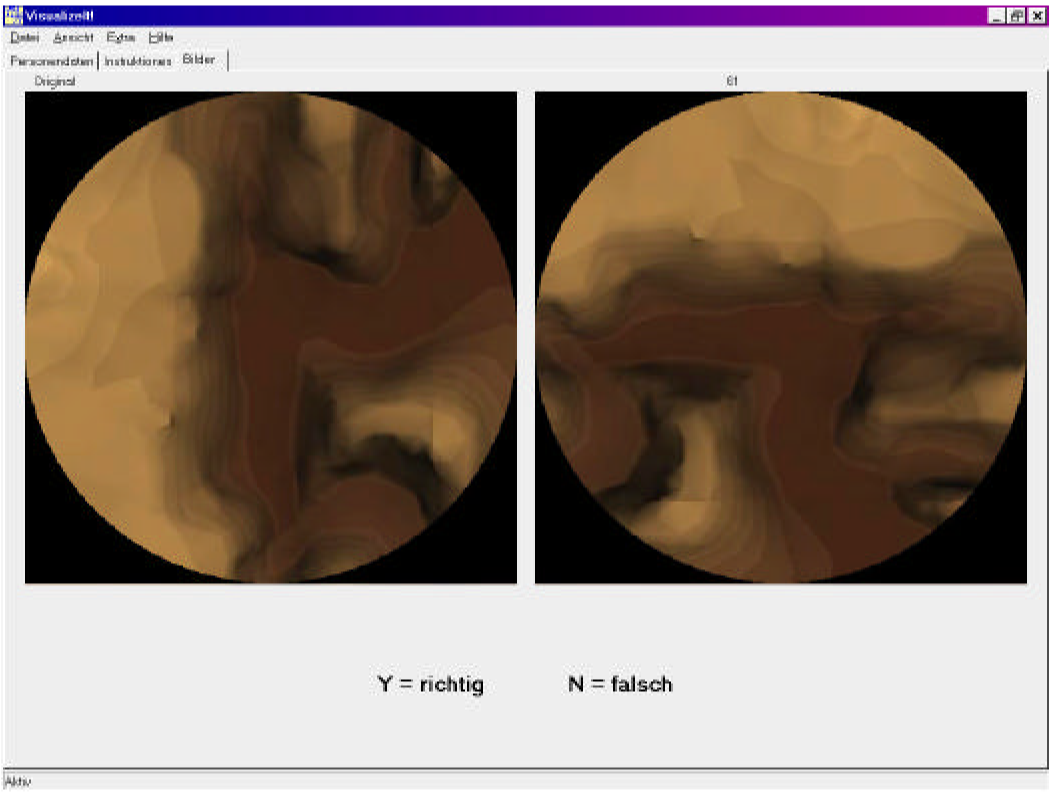


Figure 84 Screenshot of Set No. 61 layered Depiction by Bauhaus [Bau00[76]]

Instructions

Subjects of both samples could read the following instructions on the screen:
“Thank you for your participation
The objective of this experiment is the assessment of terrain visualisation. Soon you will see several sets of two pictures. They show an extract from a terrain visualisation.
Your task is to detect whether the right picture is a rotated or rotated and reflected version of the left picture. If you think that this picture is reflected and possibly rotated, please press button “N”. If you think that the picture is only rotated please press button “Y”. Please try to find the correct answer as quickly and as precisely as possible. However, you will not get a response as to whether your answer is right or wrong. The experiment is separated into nine blocks. The first block is a test trial. Between two blocks you may relax before continuing by pressing any key.”

If the subjects had no questions they could start the experiment by pressing any key.

Procedure

Subjects had the possibility of choosing a date within a time table. The presentation of linear and layered terrain was alternating. Subjects were guided to the PC and adjusted their seats. The experimenter closed the curtain and subjects began to fill in their personal data. The questions concerned gender, age and profession. After the confirmation, the instruction page appeared. Subjects had enough time to read the instructions carefully. If there were any questions, the experimenter explained the instructions once more. The use of the buttons was emphasised again and after a button was pressed, the first 20 test trials began. Subjects could decide how long they needed for relaxation. Now the experiment consisting of eight blocks of 20 sets each began. The experimenter was outside the curtain and could be consulted in case of uncertainties. At the end, the experimenter thanked and rewarded the subject for his participation. The overall duration was between 20 and 40 minutes for each subject.

Hypothesis

Four hypotheses are split into two parts. First, the linear and the layered depictions will be compared. The objective is to quantify differences between both samples and allow conclusions to be drawn on the advantages of cognitive mapping. The second part will analyse the learning behaviour during the experiment.

All hypotheses will be tested to the 95% significance level and some will be tested to the 99.9% level which indicates very significant results.

Comparison of linear/layered Depictions

A is a directed difference hypothesis:
$H_{1,A}$: The number of hits for the layered depiction is higher than for the linear depiction.

This hypothesis is based on the fact that strong patterns simplify the comparison of the two stimuli. Simplify means they allow subjects to objectify the identity of images.

B is a directed difference hypothesis:
$H_{1,B}$: The response time for the layered depiction is lower than for the linear depiction.

This hypothesis is based on the idea that the layered depiction offers distinct patterns to be detected very quickly. In contrast, the linear depiction requires more effort in detecting patterns and rotating them.

Learning

C is a directed correlation hypothesis:
$H_{1,C}$: The response time decreases during the experiment.

Anderson describes the correlation between response time and number of trials; the power law of learning [And94[77]]. He mentioned that plotting the logarithm of response time and the logarithm of number of trials results in a straight line. This implies that the learning effect is very strong in the beginning and gets smaller and smaller during the experiment.

D is a directed correlation hypothesis:
$H_{1,D}$: Training transfer between stimuli is possible.

The confirmation of hypothesis C might be caused by the familiarisation of the subject with the twelve selected locations. The decrease of response time may be due to the fact that they see these locations several times. However, as mentioned above, the first 20 test trials consist of three pictures which will not appear in the following blocks. If training transfer is not possible between different locations, the necessary response time will have a step between the test trial and the trial. If training transfer is possible, points in the logarithmic plot will fall very close to a straight line.

3.1.3 Results

Response times as well as answers of each subject and each trial (180 per subject) were merged into one data set. This set was converted into a data format that allows importation into the English SPSS for windows version 9.0. Further on, **S**tatistical **P**ackage for the **S**ocial **S**ciences (SPSS) will be used for statistical treatment.

3.1.3.1 Data Cleaning

Due to too many errors and a procedural error, two data sets had to be left out of consideration. These were the sets of subject No. 24 and 34. Furthermore three data sets were inverted due to a misinterpretation of instructions (subjects No. 6, 17, 19). The measured time of picture 45 of subject No. 22 was replaced. Instead of 120s the average value of 8.14s was inserted since this runaway was probably not caused by the presented material.

Response times as well as the number of correct answers were standardised.

3.1.3.2 Comparison of linear/layered Depiction

For this comparison and its analysis, the results of the 20 test trials were not taken into consideration. Thus, for each subject, we used 160 response times and answers.

Number of correct Answers

The number of hits is standardised which results in a mean of 0,79 or 79% for the linear depiction and 0,92 or 92% of correct answers for the layered terrain depiction (Table 3). This difference of 13% is impressive. Analysed in a t-test for independent samples, the 2-tailed significance is about 99,6% as you can see in Table 4. This confirms hypothesis A, that the number of correct answers is higher for the layered terrain depiction.

	Hits	
	Terrain	
	linear	layered
N	16	16
Mean	,788281	,919922
Std. Deviation	,152580	5,8E-02
Std. Error Mean	3,8E-02	1,5E-02

Table 3 Group Statistics of Correct Answers

Figure 85 and Figure 86 show the histogram and normal distribution of the number of subjects over hits. On the one hand, the mean of the distribution for the layered terrain is shifted to the right caused by the number of correct answers. On the other hand, the distribution of the linear terrain is broader caused by the high standard deviation. It should be mentioned that the normal distribution is only a good approximation of the sample.

			Hits	
			Equal variances assumed	Equal variances not assumed
Levene's Test for Equality of Variances	F		14,962	
	Sig.		,001	
t-test for Equality of Means	t		3,224	3,224
	df		30	19,292
	Sig. (2-tailed)		,003	,004
	Mean Difference		,131641	,131641
	Std. Error Difference		4,08372E-02	4,08372E-02
	95% Confidence Interval of the Difference	Lower	4,82400E-02	4,62551E-02
		Upper	,215041	,217026

Table 4 Tests for Independent Samples

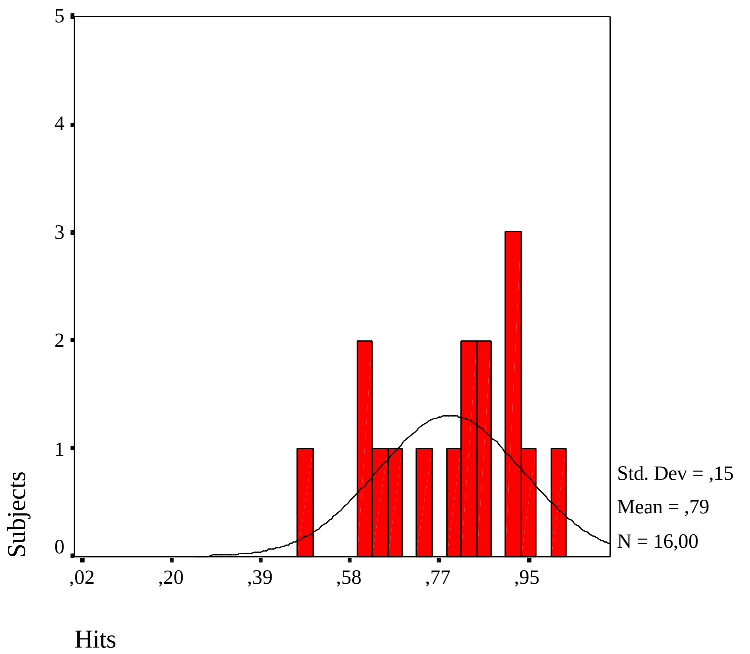


Figure 85 Histogram of Subjects over Hits for the linear Terrain Depiction

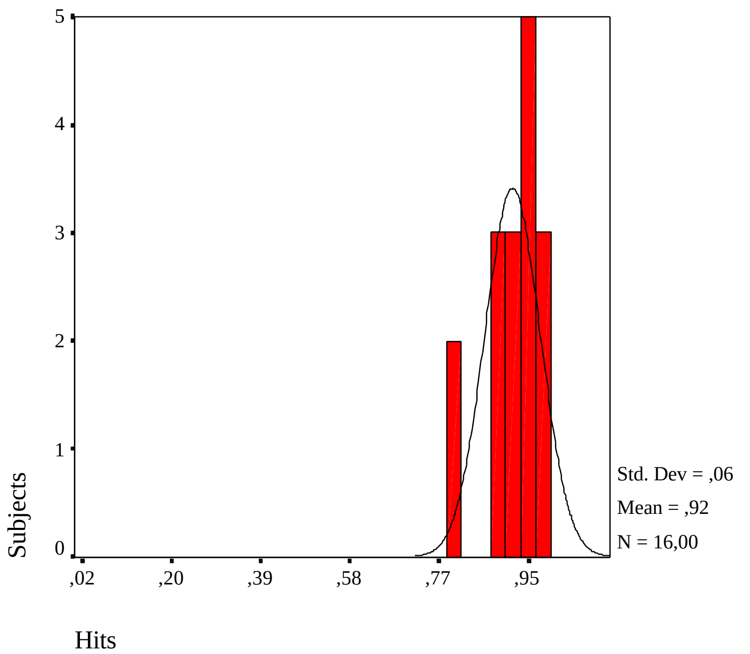


Figure 86 Histogram of Subjects over Hits for the layered Terrain Depiction

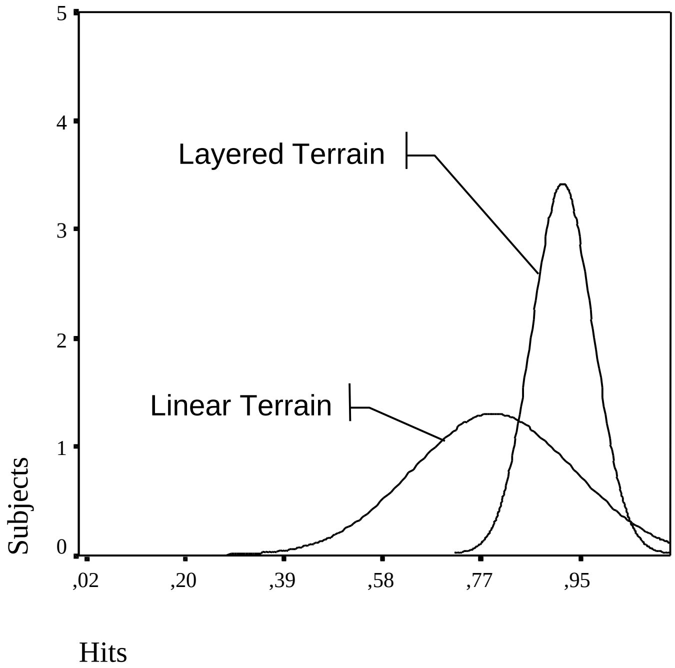


Figure 87 Comparison of Hits of linear/layered Terrain Depiction.

Figure 87 compares the distribution for both terrain depictions in one diagram. This figure illustrates the advantage of the layered depiction. The recognition of a topographic characteristic on a rotating digital map is much easier if contour layers are depicted.

The high significance was confirmed with ANOVA, too.

Response Time

In contrast to hypothesis B the average response time for the layered depiction was about 0,4 s slower than the average response time of 4,92 s for the linear depiction. This result suggests that hypothesis B should be rejected (Table 5).

	Time [s]	
	Terrain	
	linear	layered
N	16	16
Mean	4,916867	5,285922
Std. Deviation	1,799096	1,655541
Std. Error Mean	,449774	,413885

Table 5 Group Statistics of Response Time [s]

			Time [s]	
			Equal variances assumed	Equal variances not assumed
Levene's Test for Equality of Variances	F		,203	
	Sig.		,655	
t-test for Equality of Means	t		,604	,604
	df		30	29,795
	Sig. (2-tailed)		,551	,551
	Mean Difference		,369055	,369055
	Std. Error Difference		,611226	,611226
	95% Confidence Interval of the Difference	Lower	-,879236	-,879597
		Upper	1,617346	1,617706

Table 6 Tests for independent Samples

Table 6 shows that this result is not significant which could be expected due to the high standard deviation. Hypothesis B has to be rejected, but the contrary hypothesis $H_{0,B}$ is not more likely as a result. The histograms as well as the normal distributions of these results are shown in Figure 88 and Figure 89.

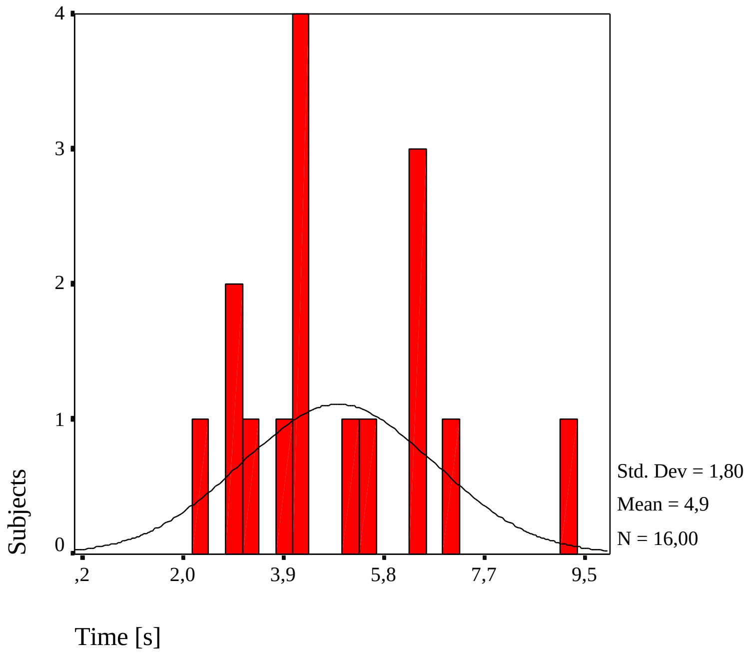


Figure 88 Histogram of Subjects over Response Time [s] for linear Terrain Depiction

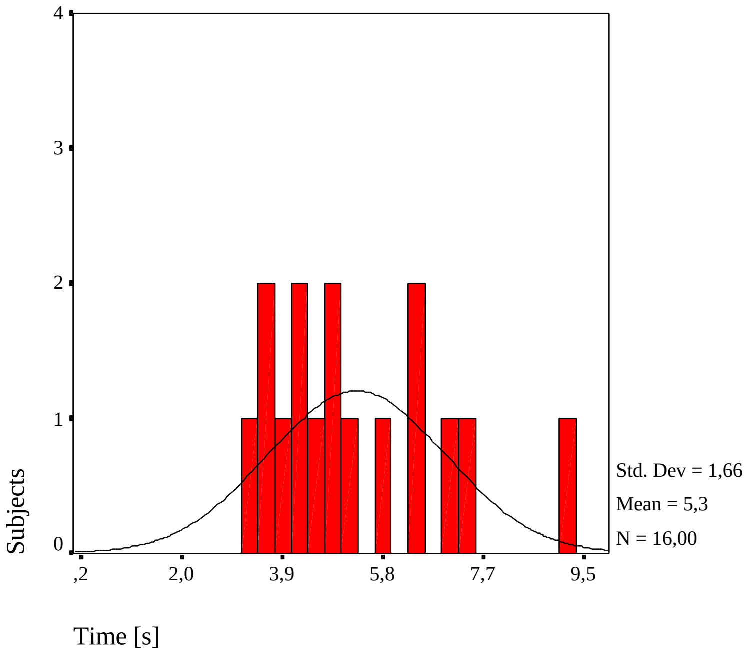


Figure 89 Histogram of Subjects over Response Time [s] for layered Terrain Depiction

Since the number of hits was significantly higher for the layered depiction we expected a correlation between the number of hits and the necessary response time. This expectation was confirmed with the Pearson correlation test. For the linear depiction there is a positive correlation between both dependent variables at a very high significance level of 99,9% (Table 7). This means that the fewer hits a subject performed the less time he needed, or the more hits he performed the higher his response time.

		Time [s]
Hits	Pearson Correlation	,739**
	Sig. (2-tailed)	,001
	N	16

Table 7 Correlations of Time and Hits for the linear Terrain Depiction

This result was analysed in SPSS with a quadratic regression. We decided to test a quadratic regression instead of a linear one, because the linear one would imply more hits than possible (>100%) at a certain response time. The choice of the quadratic regression was confirmed by the high significance of 99,7% (Table 8).

b_0 describes the intersection, b_1 the slope and b_2 the quadratic value.

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
Hits	QUA	0,592	13	9,45	0,003	0,2353	0,1623	-9E-3

Table 8 Quadratic Regression of Hits-Time Correlation for linear Terrain Depiction

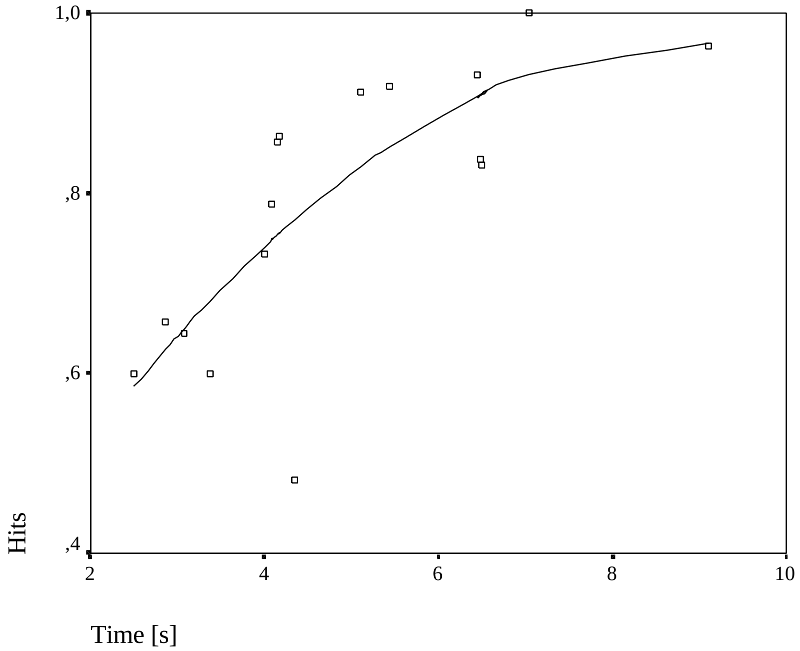


Figure 90 Quadratic Regression of Hits-Time Correlation for linear Terrain Depiction

Figure 90 visualises this result. The 16 markers show the measured data. The marker close to the vertical axes, for example, represents a subject that had a mean response time of 2,3 s at about 60% of correct answers. The curve indicates the approximated quadratic correlation between hits and response time.

The same analysis was performed for the layered depiction. As you can see in Table 9, there is no significant correlation between response time and number of correct answers.

		Time [s]
Hits	Pearson Correlation	,341
	Sig. (2-tailed)	,196
	N	16

Table 9 Correlations of Time and Hits for the layered Terrain Depiction

In order to compare the Pearson correlation we realised a Fishers z-transformation which indicated that the correlation for the linear depiction is three times higher than for the layered one (0,948 instead of 0,355). This result of low significance was confirmed by the quadratic regression shown in Table 10. Again Figure 91 shows the subject markers as well as the quadratic regression curve that is close to a straight line.

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
Hits	QUA	0,116	13	0,86	0,447	0,8542	0,0128	-7E-05

Table 10 Quadratic Regression of Hits-Time Correlation for layered Terrain Depiction

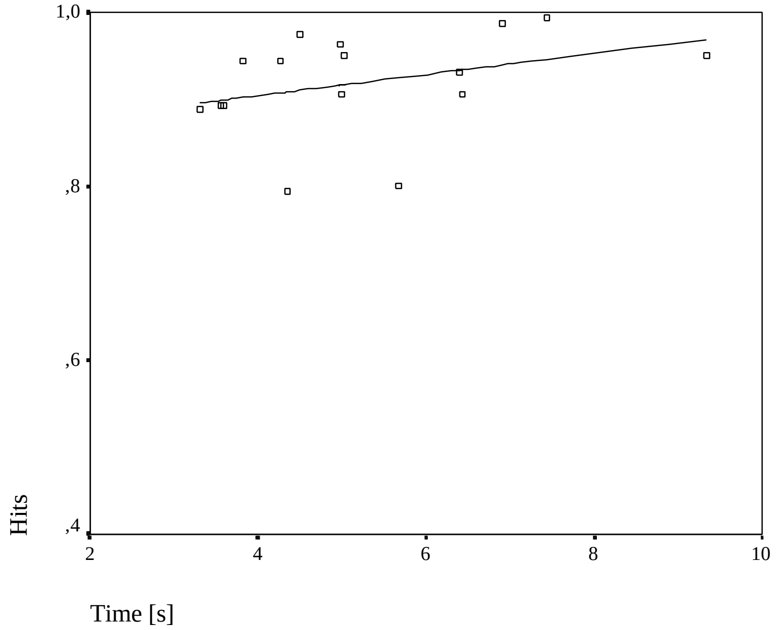


Figure 91 Quadratic Regression of Hits-Time Correlation for layered Terrain Depiction

Figure 92 simplifies the comparison of both curves. On the one hand you will see that the number of correct answers for the layered depiction is always higher. However, both curves seem to intersect between 8 s and 10 s of response time. Marker A indicates the mean response time (5,28 s) and mean hits (92%) of the layered depiction. Marker B indicates the number of hits performed with the same response time for the linear depiction. This shows that subjects reached about 9% fewer hits which fits to the results we found before. If a subject using the linear depiction should reach the same number of hits, he would need about 6,65 s (Marker C) which is 26% more than subjects using the layered depiction.

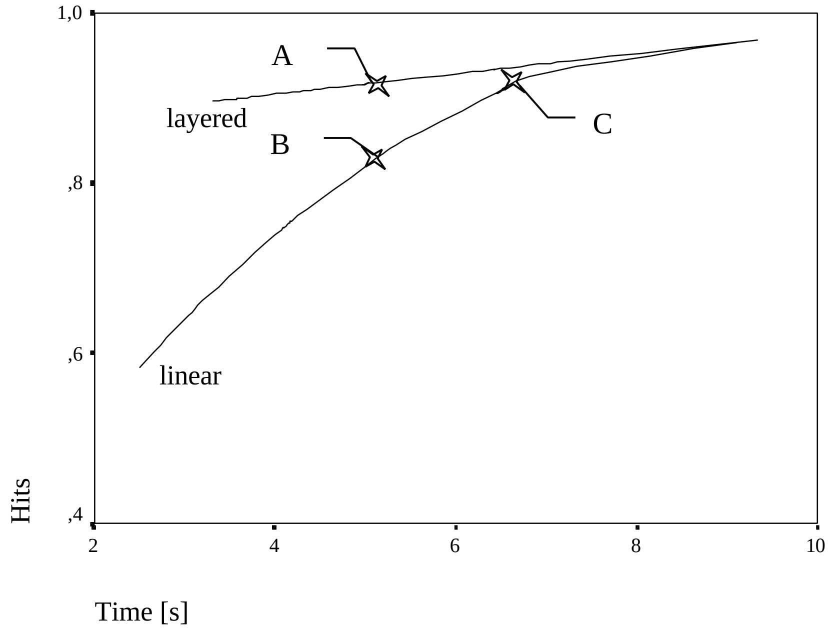


Figure 92 Comparison of Correlations of the Linear and the layered Terrain Depiction

3.1.3.3 Learning

For the analysis of training effects the first 20 test trials were included since they illustrate the training effect. Thus, for each subject we analysed 180 response times. 20 response times were grouped together representing one block. For this analysis the SPSS procedure “repeated measures” was used. For the further analysis the two samples were merged together since they had similar characteristics.

Figure 93 shows the response time over the number of trials. During the test trial subjects needed about 6,4 s which decreased during the experiment to less than 5 s. This supports hypothesis C that learning is possible. The power law of learning makes us expect a straight line if the logarithms of number of trials as well as response times are plotted. This correlation is shown in Figure 94. All markers fall on the straight line which proves hypothesis C. As mentioned above, the learning effect might be caused by familiarisation with the presented material. However, since the material of the test trial was not used in the further experiment and the material in the last 160 trials was not presented in the first 20 trials, hypothesis D is also confirmed. If there was no training transfer, the marker N = 30 would have a response time of 6,4 s instead of 5,7 s.

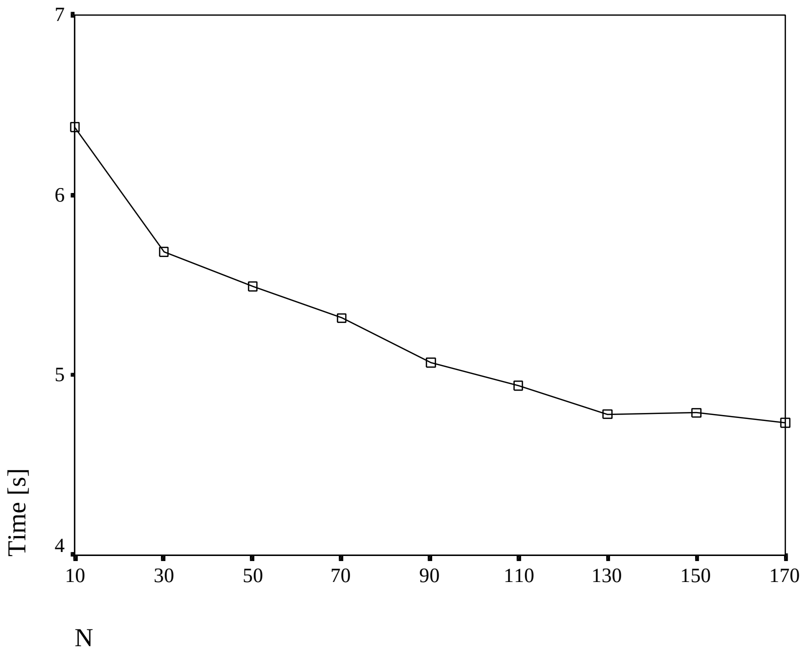


Figure 93 Response Time [s] over a Number of Trials for one Sample

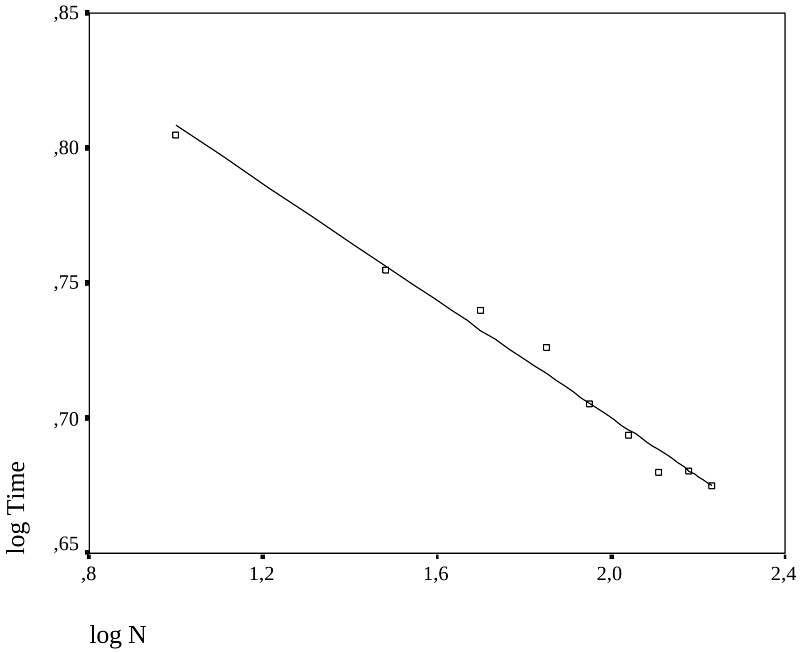


Figure 94 The Power Law of Learning

3.2 Summary

The objective of this thesis was the development of a terrain presentation for a synthetic vision system that takes human requirements into account. It was based on the hypothesis that the absence of a cognitive map during or after the use of the Cavok flight guidance displays is due to the poor adaptation of terrain presentation to cognitive requirements of the human. Improvement of perception and cognition of synthetic spatial environment allows the creation of a cognitive map even in this environment.

Psychological requirements concerning perception and cognition were analysed in detail and served as design criteria for a new terrain presentation. This new terrain presentation proved to significantly facilitate perception and cognition. An extensive pattern recognition experiment was performed, which proved that mental rotation can be executed much faster and with fewer errors. This tremendous advantage was proved for an intermediate result, since the final terrain presentation including contour layers and contour lines did not exist at that time. It is expected that there is an additional improvement in presenting this final terrain model.

An expansive database is available for further research on cognitive mapping in synthetic environments.

3.3 Outlook

Controlled Flight into Terrain is the major cause of accidents in aviation today. Loss of situation awareness is the reason. The Cavok flight guidance displays have been evaluated in several simulator and flight tests and were rated excellent concerning situation awareness and controlled flight into terrain avoidance. However, the implementation into operational use has to be assessed under safety as well as economical aspects. What is the trade-off? The trade-off at a first glance is the necessary redesign of training and education of pilots. This is in contrast to well established family concepts that minimise necessary type ratings, for example [Kra97[78]] [Sta98[79]].

However, there are major advantages if the training is adapted to the opportunities the new terrain depiction offers to the pilot.

Looking at commercial flight schools, training sections can be distinguished into:

- Basic airmanship skills
- Procedural skills
- Aircraft specific knowledge (Type rating)
- Location specific knowledge (Airport familiarisation)

First, students have to learn how to handle an aircraft from gate to gate, including all flight phases like taxi, takeoff, landing, etc.. Pilots are trained until the necessary cognitive level is decreased from knowledge based to skill based behaviour reducing the mental effort [Ras87[80]]. Now the student has the skill to fly any aircraft in principle. However, he is not able to fly the aircraft under any weather condition e.g. in IMC. He will learn this during a special procedure training. At this point, he has the basic knowledge for flying a typical aircraft to any destination. Even if family concepts are state of the art for modern commercial aircraft, specific knowledge is necessary and is provided in type ratings. In these type ratings, the student learns to operate the different aircraft systems during normal and abnormal situations.

Standard **I**nstrument **D**epartures (SID) and **ST**andard **A**rrival **R**oute (STAR) have a standardised structure, but nevertheless, pilots must receive specific knowledge training during airport familiarisation. Junior pilots, as well as experienced captains have to inform themselves about an airport before flying to it for the first time. **C**omputer **B**ased **T**raining (CBT) helps them to get familiar with the airport environment and the departure and approach procedures. One important section of airport familiarisation is getting an overview of the airport location. This overview may start with a picture of the continent the destination is located on and then get into detail showing the spatial environment including mountains and obstacles in the airport vicinity. This part helps the pilot to create a cognitive map which is a basic requirement for strategic spatial awareness as mentioned above. The cognitive map will serve as a spatial context into which all further information like airport infrastructure will be integrated.

Comparing the information the pilot gets during training with the information available on board reveals a significant gap between the two. In good weather conditions he can compare his present outside view with the cognitive map created from slides during CBT lessons. In adverse weather conditions he has to be aware of his situation by comparing conventional PFD and ND information with the cognitive map he has created. This is a very demanding task which may result in a CFIT accident in high workload situations. Another important point is that the cognitive map stays at the same level when approaching an airport always in adverse weather condition. Moreover the cognitive map may even get worse [Hel99[81]].

Highlighted: *The pilot has to create a multi-media puzzle from information that is not correlated directly*.

3.3.1 An integrated training concept

Flying a SVS equipped aircraft will result in an increase of spatial awareness, because the actual situation is intuitively perceivable. The first approach to an airport, in training as well as in reality, will automatically result in the creation of a cognitive map of the environment. The cognitive map will be updated during further approaches and its accuracy will increase. Knowledge based on experience can immediately be used on board since the type of information is corresponding.

An integrated training concept using a terrain database like the one proposed for any kind of training as well as on board will significantly increase situation awareness and thus flight safety. Airport familiarisation, simulator visuals and charts (if not totally replaced by electronic devices) and finally onboard instruments like the Cavok flight guidance displays should all be based on this terrain depiction model allowing the pilots to create a common cognitive map.

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Studienarbeiten are documents available at:

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