Integration of Visual Metaphors in an Anesthesia Monitor

Kai van Amsterdam

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Human-Machine Communication
Dept. of Artificial Intelligence,
University of Groningen, the Netherlands

Internal supervisor
Dr. F. Cnossen
Department of Human Machine Communication
University of Groningen, Groningen

External supervisor
Dr. A. Ballast
Department of Anesthesiology
University Medical Centre Groningen, Groningen

university of groningen

umcg

Abstract

Anesthetists maintain a stable health in patients during surgery. They keep track of patient variables on the monitors and subsequently determine the appropriate treatment. In current anesthesia practice, a substantial amount of anesthesia-related accidents is due to human error in monitoring (Cooper et al. 1984). In this thesis we studied the influence of metaphors in a patient monitor on the monitoring behavior in anesthetists. We presented anesthetists and anesthesia residents with a new kind of patient monitor. This new monitor represents patient information visually as colored rectangles where height and width are proportional with the variable's value. Each rectangle is situated in a frame that represents the steady-state value of that variable for the patient. These visualizations of patient variables are called "metaphors" and they provide the anesthetist with additional information compared to the numerical values and curves in a classic anesthesia monitor. We hypothesized that a monitor with metaphorical patient information would decrease anesthetists' recognition time of complications in a monitoring task.

In a static monitoring task, anesthetists and anesthesia residents were presented with screenshots of the monitor that displayed anesthesia-related complications. Subjects responded when they recognized the complication that was presented. Subsequently, subjects were asked to select a method of medication and diagnosis for the displayed complication. Five types of monitors were presented to the subjects; classic, metaphorical (MAI), metaphorical with trend arrows (tMAI) and 2 redundant monitors (classic and MAI, classic and tMAI). The results showed no significant decrease in response times for the metaphorical monitor compared to the classic monitor. There was also no difference in response time for the trend versus the no-trend monitor types as well as in the redundant versus the single monitor types. More than forty percent of complications in the trials were identified incorrectly; therefore more research is needed to evaluate the metaphorical monitor in less complicated tasks.

Computers are incredibly fast, accurate, and stupid.

Human beings are incredibly slow, inaccurate, and brilliant.

Together they are powerful beyond imagination.

Albert Einstein (1879-1955)

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Chapter 1. Introduction

In the medical field, there is a continuous demand for improvements in patient care. Hospitals aim to increase patient safety by reducing complications that occur in the medication process. For example, prescription errors for drugs should be prevented by making sure that the prescription system warns the physician for overdoses of drugs that can lead to adverse drug effects (Does, 2009). To improve patient care, educational programs are constantly reviewed to teach medical students the latest techniques for optimal patient care. At the same time hospitals strive to increase efficiency in these procedures in order to medicate more patients in less time. In today's hospitals, technical equipment often supports physicians in their daily routine. Medical equipment is used to display physiological measurements, register patient dossiers or automatically administer medication in the patient (Kaushal et al. 2001). Progression in the technical field provides the medical practitioner with new possibilities in medication techniques and therefore, can play a major part in improving patient care.

The use of technical equipment can also increase efficiency in the hospital: computers obtain medical records over the network with the click of a button, which ideally is much faster than manually sending those records through the hospital. Errors in medication prescriptions are prevented by computerized entry-forms (Kaushal et al. 2001; Does, 2009). Technical equipment has become an extension of the current physician; with increasingly complex operations, a machine can operate more accurately, consistently and faster compared to a human.

Technological developments such as X-ray, MRI machines or patient monitors help physicians in better care for patients, but at the same time, they also provide a challenge in communication between user and machine. Technical equipment is capable of executing complex actions or storing large amounts of data only when given instructions from a user. At the same time, the machine must also display measured information on a monitor in a human-readable format to help the user with the interpretation of these data. Misinterpretations in the communication between user and machine can lead to inefficiency in the medication procedure and even death of the patient as a result of wrong settings in the machine (Cooper, 1984).

Human Machine Communication (HMC) studies the interaction between humans and machines from a psychological and cognitive point of view. Computers have a very different approach in “reasoning” compared to humans; every calculation in a computer follows strict logical rules, whereas humans can reason in a more intuitive manner (Tversky & Kahneman, 1974). The main goal of HMC is to find solutions for communication errors between humans and machines. These solutions consist of increasing usability in machines by studying human behaviors in operating these machines, or by modeling human behavior to gain knowledge about mental processes in executing a task. The main goal in HMC is to obtain optimal performance from both human and machine.

In this thesis, we focus on improving human-machine communication in Anesthesiology. In this medical field, technology plays a major role in supporting the anesthetist in his/her tasks. Errors in human-machine communication can have catastrophic effects on the patient’s health (Lagasse, 2002; Amalberti et al. 2005). Anesthesiology is a medical field where problems in human-machine communication are extensively studied (Leape, 1994; Fung & Cohen, 1998). Current research in anesthesia-related errors focuses on the anesthetist in interaction with his/her equipment (Gaba, 2000). During surgery, anesthetists watch the patient monitors to check the health status of the patient. These monitors provide the anesthetist with a continuous stream of patient information. Misinterpretation of these patient information or missing pieces of information can lead to wrong diagnoses and are a potential hazard for the patient’s health (Weinger & Englund, 1990).

In this thesis we study anesthetist’s monitoring behavior. We developed and tested a new patient monitor that is designed from a HMC point of view.

1.1. Structure of the thesis

This thesis is divided into four parts: the job of the anesthetist in the operating room, past research, development of a new anesthesia monitor and we present an overview of the monitoring experiment. The job of the anesthetist in the operating room outlines the different tasks that anesthetists perform during surgery. We also discuss the anesthetist’s equipment and we present an overview of vital physiological variables that anesthetists keep track of. In past research, we discuss studies that focus on models of cognitive processes known in Psychology. These models describe human behavior in complex systems such as aviation and anesthesia. Further, we present research for development of technical equipment for anesthetists and advancements in patient monitoring. In chapter 5 we present the results of our pilot research on which the new anesthesia monitor is based. The design considerations for this new monitor are outlined in chapter 6. Finally, in chapters 7-9, we provide an overview of the monitoring experiment. This experiment was performed with anesthetists and anesthesia residents to test whether the new metaphorical monitor helped subjects to recognize complications faster compared to the classic anesthesia monitor. We describe the experimental setting, results and finish with a discussion of the experiment.

Chapter 2. Background

The main goal of the thesis is to investigate the occurrence of human error in patient monitoring and to develop and test a new type of patient monitor. To get a basic understanding of the complexity of the anesthetist's job, we start this thesis with an overview of the various tasks of the anesthetist in the operating room. Chapter 2.1. discusses the admission of anesthesia and the influence of different body systems on the patient's health. In chapter 2.2. we provide an overview of the monitors and the different patient variables that are displayed.

2.1. Job of the anesthetist

Anesthetists are involved in the entire operation process: from the first admission of anesthetics to the recovery of the patient after surgery. An anesthetist makes sure that a patient is ready for surgery by reassuring and checking the emotional status of the patient. The word *anesthesia* in this thesis depicts *general anesthesia*. With local anesthesia, the patient remains conscious and is able to talk with the anesthetist. For a general anesthesia, the patient is injected with muscle relaxants, hypnotics and pain blockers. Due to the loss of control over the muscles, the patient is not able to breathe autonomously. The anesthetist manually controls the patient's breathing while the patient reaches unconsciousness. An endotracheal tube is placed in the patient's trachea. Through this tube, the patient is ventilated with a machine and is now ready for surgery.

In the patient, numerous responses to the surgical activities can occur, such as increased heart rate, loss of body fluids, allergic reactions or sudden rise in temperature; these complications can result in discomfort, injuries or death. To control physiological responses from the patient, the anesthetist administers certain anesthetics to suppress the patient's self-protecting reflexes and thus keep physiological imbalance to a minimum. The human body is a complicated system, where small changes in physiology can eventually result in major complications (Gaba et al. 1987).

The current operating room is equipped with a variety of technical equipment that is wired to a patient. To monitor the patient's health status, the anesthetist has to rely almost entirely on monitors. The monitors display data from a variety of measurements such as heart rate, oxygen saturation of the blood and amount of CO_2 in expired air. In traditional anesthesia monitors, measurements are presented by numerical values and small trend curves. Measured patient variables are part of the respiratory system, cardiovascular system, body fluids or administered anesthetics.

With the occurrence of complications the anesthetist usually interprets the patient variables to make up several diagnoses (i.e. differential diagnoses). The anesthetist selects the diagnosis he/she thinks is the most plausible in this situation and chooses an appropriate treatment to test this hypothesis. When complications are immediately life threatening, the patient is treated symptomatically before an exact diagnosis can be identified. Therefore, the anesthetist has the authority to stop the surgical procedure when the health of the patient is highly at risk. Anesthetists are in a continuous process of monitoring a multitude of physiological systems and adapting their treatments to the current diagnosis. The systems that are most vital for the patient's health are discussed below.

Respiratory system

A fully anesthetized patient cannot breathe autonomously, thus the anesthetist provides the patient with oxygen through an endotracheal tube to keep the body oxygenated. Insertion of an endotracheal tube is called intubation and is executed during induction (i.e. the preoperative process, where a patient is anesthetized and prepared for surgery). The ventilator machine pressurizes air through the tube into the patient's lungs for inhalation and depressurizes to remove the deoxygenated and carbohydrated "used" air from the lungs for exhalation. The anesthetist controls respiratory rate (i.e. rate of inhalation/exhalation per minute), the mix of the different inhalational gases (i.e. normally a mix of O_2, air and volatile anesthetics) and pressure of air in the lungs and airway.

Cardiovascular system

The cardiovascular system consists of all parts of the human body that carry blood or lymph. Blood flows through vessels; the heart pumps the blood through the arteries to the veins, from the capillaries into the organs and ultimately to the veins. The bloodstream provides the body with nutrients and oxygen, but also carries waste matter away from the organs. There is a strong relation between the vascular system and respiratory system; Oxygen from the air is being transferred in the bloodstream through the lungs. Deoxygenated blood flows back from the organs to the lungs, where excess CO_2 is breathed out through the lungs.

Body fluids

Sixty percent of the human body consists of water. This water is used to transport nutrients and waste products through the body. During surgery, the body loses fluids through sweating and bleeding. Especially large open wounds can lead to evaporation of large amounts of body fluids. When the patient loses blood, this can be dangerous because fewer nutrients are transported to the organs and less waste products are transported away from the organs. This could lead to malfunctioning of organs or even complete organ failure. The anesthetist is monitoring the patient's fluid balance during surgery. When the patient loses too much fluids, the anesthetist can administer blood into the vascular system intravenously. Normally, an infuse is attached to a patient during surgery, to keep the fluids in balance.

Administered anesthetics

Anesthetics are administered to sedate the patient. General anesthetics can be administered in two ways: intravenously (i.e. directly into the bloodstream) and through inhalation. Normally, in current anesthesia practice, anesthetics are administered intravenously, because the most effective anesthetics nowadays are fluids (e.g. Propofol). Anesthetists use a combination of anesthetics to relax muscles in the patient, induce sleep and block transmission of pain responses. Relaxation of the muscles in the patient allows the surgeon to access the target area, but has as a negative side effect that it also prevents independent breathing of the patient, thus during general anesthesia, the patient's lungs are ventilated mechanically.

The level of anesthetics can be controlled manually or automatically. When the patient needs a large amount of anesthetics in a short time, this is normally administered by manual injection. In the operating theatre, the anesthetist can also use automatic anesthetic pumps to administer an amount of anesthetics intravenously at a preset rate. When a patient is on the automatic pump, a constant degree of anesthesia can be maintained during a longer period of time.

2.2. Current patient monitoring in Anesthesia

In the operating theatre, anesthetists normally view two types of monitors: the patient monitor (Fig. 1) and the ventilator's monitor (Fig. 2).

The ventilator machine pumps a gas mixture (O_2, air and volatile gases) in and out of the lungs at a user-adjusted rate and pressure. The monitor of the ventilator presents variables such as pressures, respiratory rate and O_2 percentage. The anesthetist can directly adjust these variables with the push of a button.

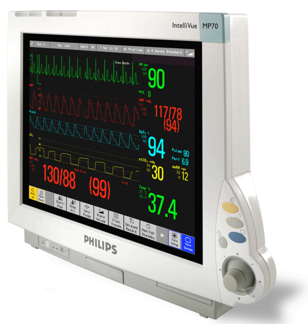

Figure 1. Philips IntelliVue mp-70

Figure 2. Dräger ventilator machine

2.2.1 Anesthesia patient monitor

In the Operation Rooms of the UMCG anesthetists currently make use of the Philips MP-70 IntelliVue monitor (Fig. 1) for patient monitoring. This monitor displays curves for ECG, Plethysmogram, Capnogram and Ventilation pressure. The values displayed and most used are: heart rate, blood pressure (systolic, diastolic and mean), saturation (SPO_2), end tidal CO_2, PEEP, PAW and BIS value. In the next paragraph, these variables will be explained. The patient monitor is adjustable to personal taste: anesthetists can alter the colors of the curves and values, replace data to another part of the display and show trend curves for each variable. Although there is a great flexibility in presentation possible for this monitor, most anesthetist use roughly the same display. The patient monitor presents all measured physical responses from the patient's body that are normally displayed as a value and/or a curve. In the next paragraph, we will describe the most important physiological variables that are represented in the patient monitor. These variables are also displayed in the new metaphorical anesthesia interface that is presented in chapter 6.

2.2.2. Values presented on anesthesia monitors

For all displayed variables we discuss its influence on the patient's health. We present the steady-state values for all variables, because these are important in the development of the new metaphorical interface (chapter 6). Steady-state values are based on a specific patient profile, commonly used as a reference in the medical field: man in rest with height, 1.78 meters and weight, 70 kilos. The steady-state values for the variables were obtained in dialogue with an experienced anesthesiologist.

Oxygen saturation

When air flows into the lungs, O_2 is dissolved in the bloodstream where it is transported to the organs in the body. Organs need to be oxygenated to function properly. To measure oxygen saturation, the anesthetist can use a pulse oxymeter. This device measures the amount of oxygen in the patient's pulsating blood by obtaining the absorbance of red and infrared wavelengths through the patient's skin. The pulse oxymeter is usually placed on the earlobe or thumb of the patient, because on these limbs the skin is relatively thin. In traditional monitors, Oxygen saturation is displayed as SPO_2 (Saturation Pulsation O_2). For a male patient in rest (1.78 m, 70 kilos), a SPO_2 steady-state value of ≥95% is considered normal; levels below 95% are considered critical.

Heart rate

Heart rate is the number of heartbeats per minute. With each contraction of the heart, oxygenated blood streams to the organs and deoxygenated blood flows back to the lungs. Changes in heart rate can be a reaction to pain or to the effects of anesthetics in the body, thus heart rate is a vital sign of the patient's health status. Heart rate is usually measured non-invasively by the placement of electrodes on the patient's chest. These electrodes measure the number of heart pulsations per minute. Heart rate can also be calculated with the pulse oxymeter, via intra-arterial cannula (which will be outlined in the next paragraph) or by manual checking the patients' pulse at the wrist. For a male patient in rest (1.78 m, 70 kilos), a heart rate steady-state value of 75 bpm is considered normal; levels below 50 bpm and above 110 bpm are considered critical.

Blood pressure

Blood pressure is the pressure that blood exerts against the walls of the arteries. Hypertension (blood pressure that is too high) and hypotension (blood pressure that is too low) both indicate that the body is in a physical imbalance. Blood pressure can be measured invasively or non-invasively.

In the operating theatre, the blood pressure is usually measured non-invasively by placing a Riva-Rocci cuff around the upper arm. Blood pressure can be measured invasively by using a cannula (i.e. arterial line) that is inserted into an artery. Invasive measurement of blood pressure is more accurate but causes more inconvenience to the patient. The advantage of an arterial line is that the anesthetist can measure blood pressure continuously while gathering blood samples from the patient through the line.

An anesthetist measures systolic and diastolic blood pressure. Systolic blood pressure is the peak pressure in the arteries that occurs at the end of a cardiac contraction. Diastolic pressure is the minimum pressure in the arteries and occurs just before the next cardiac contraction. The values of blood pressure are measured in millimeters of Mercury (mmHg). The steady-state blood pressure for a male in rest (1.78 m, 70 kilos) is approximately 120/80 (120 mmHg systolic, 80 mmHg diastolic); levels of systolic blood pressure below 60 mmHg and above 200 mmHg are considered critical.

Inspired O_2

The ventilator machine drives air into the lungs and the anesthetist controls the O_2 concentration in the air mixture. The inspired O_2 concentration is a parameter setting of the ventilator machine, but is also measured in the delivered gas mixture. The steady-state O_2 for a male in rest (1.78 m, 70 kilos) is approximately 45%; levels of O_2 below 35% are considered critical.

Expired CO_2

At exhalation, air is driven from the lungs back into the ventilator machine. The concentration of O_2 in the expired air is lower than in inspired air, because the body consumes O2. The CO_2 concentration in the expired air is measured in mmHg or kPa (kilopascal). A low CO_2 concentration can indicate that the body is not able to transport the necessary amount of CO_2 to the lungs. This could be caused by a range of failures in blood circulation or errors in the oxygen supply. The steady-state CO_2 for a male in rest (1.78 m, 70 kilos) is approximately 4.3 kPa; levels of CO_2 below 3.3 kPa and above 5 kPa are considered critical.

PEEP and PAW

The ventilator machine drives air into the lungs with a certain pressure, known as Peak Airway pressure (PAW). At exhalation, air is driven passively from the lungs back into the ventilator machine.
The steady-state PAW for a male in rest (1.78 m, 70 kilos) is approximately 18 cmH_2O; levels of PAW below 14 cmH_2O and above 20 cmH_2O are considered critical.

Usually the machine is adjusted to keep a small positive pressure during exhalation: Positive End Expiratory Pressure (PEEP). Filling up the lungs requires a higher pressure, because gravity forces the patient's chest downwards while the lungs need space in the chest to fill up with air. The pressurized air also has to uplift the force exerted by the patient's lung partitions to make the lungs grow in volume. With exhalation, the force of gravity moves the patient's chest down and air escapes from the lungs. The PEEP prevents the lung's alveoli from total collapse; this is necessary because collapsed alveoli make re-inflation of the lungs more difficult. The steady-state PEEP for a male in rest (1.78 m, 70 kilos) is approximately 2 cmH_2O; levels of PEEP below 2 cmH_2O are considered critical only when the SPO_2 level is below 98%.

Tidal volume

The amount of air that is driven into the lungs is known as the tidal volume. The tidal volume depends on the volume of the lungs, the compliance of the lungs and the pressure setting on the ventilator machine. For instance, in a patient with a low compliance of the lungs, more pressure is needed to drive the same amount of air into the lungs than with higher compliant patient lungs. Tidal volume is presented in ml (milliliters). The steady-state tidal volume for a male in rest (1.78 m, 70 kilos) is approximately 450 ml; levels of tidal volume below 300 ml and above 650 are considered critical.

Respiratory rate

Respiratory rate is the number of respirations per minute. A respiration is a cycle of inspiration and expiration. With general anesthesia, the ventilator machine controls the respiratory rate according to the setting by the anesthetist. The steady-state respiratory rate for a male in rest (1.78 m, 70 kilos) is approximately 15 resp/min.; levels of respiratory rate below 12 resp/min. and above 20 resp/min. are considered critical.

2.2.3. Curves presented on anesthesia monitors

ECG

The ECG (Fig. 3) is the curve from measured electrical activity of the heart muscle. The interpretation of the ECG curve provides information about the activity in the left and right atrium (i.e. upper heart cavity) and ventricles (i.e. lower heart cavity). From the ECG the anesthetist can interpret whether the heart shows failures. Because the ECG measures electrical variations in the heart muscles, its measurement is easily distorted by external electrical signals. Surgical procedures with electrical equipment can disturb an ECG in such a way that the ECG heart information becomes non-interpretable. The numerical value for heart rate is usually derived from the ECG curve and displayed separately on the patient monitor.

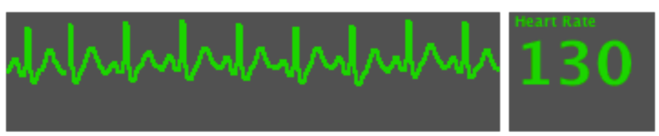

Figure 3. ECG curve and Heart rate value

Plethysmogram

The Plethysmogram (Fig. 4) is a visual presentation of the electrical signals from the pulse oxymeter. The pulse oxymeter measures oxygen saturation of the blood as well as fluctuations of the blood volume in the arterial blood vessels due to the cardiac rhythm. Peaks in the signal indicate maximum amounts of blood in the arterial blood vessels. Relative low peaks in the Plethysmogram may thus indicate a decreased bloodstream to the arterial blood vessels.

Figure 4. Plethysmogram curve and Oxygen saturation value

Capnogram

The Capnogram (Fig. 5) presents the measured CO_2 in respirated air. In the inspiration phase the CO_2 concentration in the inspired air is close to 0%. In the expiration phase the CO_2 concentration in the expired air increases. Technical failures in ventilation can cause a decline in CO_2 concentrations or other anomalies in the CO_2 signal. Tinker et al. (1989) studied anesthesia-related accidents and concluded that nearly one third of anesthetic related incidents found in an accident report would not have happened with a Capnogram and Plethysmogram integration in the monitor. The Capnogram and Plethysmogram are present in current anesthesia monitors.

Figure 5. Capnogram and expired CO_2 value

Ventilation pressure

In current ventilator machines, two types of ventilation are common: pressure-controlled and volume-controlled. In volume-controlled ventilation, the anesthetist sets the machine to deliver a certain volume of air into the lungs. The machine calculates the amount of ventilation pressure to obtain the required volume. In pressure-controlled ventilation, the anesthetist sets the required ventilation pressure manually in the ventilator machine. Most anesthetists ventilate their patients pressure-controlled to keep direct control over the ventilation pressure. To keep track of any mechanical failures in ventilation pressure, the anesthetist monitors the ventilation pressure graph (Fig. 6) and sometimes an expiratory flow graph as well. PEEP (expiration pressure) and PAW (inspiration pressure) are presented as a function of time in the ventilation pressure graph.

Figure 6. Ventilation pressure, PEEP, PAW and tidal volume values

Trend records

During surgical procedures anesthetists can also display trends for vital variables on the monitor. Variables that show a slow decline or incline can develop into complications without notice (Rowbotham & Smith, 2006). Monitors display trend information over a chosen time period in a line graph.

Chapter 3. Past research

In this chapter, we present past research in anesthetist performance on recognition and detection of anesthesia-related complications. We discuss the cognitive processes in anesthetists that can lead to errors in judgment of the patient situation. This research examines anesthetists' monitoring behavior from a psychological point of view. Next, several warning systems for anesthetists are presented, such as alarms, monitors and decision support systems. These systems were designed to support the anesthetist in recognizing complications. The research presented in this chapter serves as a basis in the development and testing of a new metaphorical anesthesia interface.

3.1. Safety in anesthesia

3.1.1. Anesthesia-related complications

Anesthesia is a relatively safe area of medical care. The safety of administering anesthesia is comparable with safety on railways, but not as safe as nuclear industry or in commercial large-jet aviation (Amalberti et al. 2005). Depending on the type of anesthesia, the risk of catastrophic anesthesia-related accidents ranges from 1 to 10 per million patient interventions, in relative healthy patients (Arbous et al. 2001; Amalberti et al. 2005). In relative less healthy patients, the catastrophic accident rate ranges from 1 to 1.5 per 10.000 patient interventions (Lagasse, 2002).

Arbous et al. (2001) studied the cause of anesthesia-related accidents in 58 Dutch hospitals. Forty-seven anesthetists participated in the survey and their records of peri-operative incidents were reported to the researchers. Incidents that led to death of the patient in the first 24 hour after surgery were studied. The results of this study showed that 15% of all mortalities in patients were anesthesia-related incidents. Significantly more peri-operative deaths occurred in less healthy patients compared to patients in better health, which is consistent with the results from Lagasse (2002). Botney (2008) stated that Anesthesia offers no direct therapeutic benefits for the patient; therefore the risks of anesthesia must be as low as possible.

The anesthesia-related complications that occur most frequently are arrhythmia (i.e. irregular beating of the heart), hypotension (i.e. low blood pressure), adverse drug effects and inadequate ventilation of the lungs (Rowbotham & Smith, 2006). Every complication has the potential to cause lasting harm to the patient, thus deviations from normal must be managed appropriately (Gaba, 1989). In the complex task of anesthetists, several factors can lead to anesthesia-related complications: equipment failures in the breathing machine or infusion pumps, communication failures between personnel or coexisting diseases in the patient (Rowbotham & Smith, 2006). In the next paragraph we will discuss the factor that is responsible of the majority of anesthesia-related incidents: human error.

3.1.2. Human error in anesthesia

Peri-operative (i.e. during operation) anesthesia-related critical incidents can occur due to human error. The definition of human error in this context is: all actions taken by an anesthetist that can lead to an incident (Amalberti et al. 2005). In anesthesia there are two categories of human error: slips and mistakes. "A slip is an action (or lack of action) performed by the anesthetist that did not occur as planned". For example, the anesthetist inserts an endotracheal tube, but places the tube bronchial instead of tracheal. "A mistake is a decision resulting in an action (or lack of action) by the anesthetist which is causally linked to a possible or actual adverse outcome" (Gaba, 1989). For example, the anesthetist makes a mistake in his/her diagnosis, which leads to administering the wrong medication. Factors that potentially lead to human error are: fatigue (Denisco et al. 1987), sleep deprivation (Owens, 2001), boredom, stress but also the type of personality of the anesthetist: some anesthetists dare to take more risks in their actions than other more conservative anesthetists (Weinger & Englund, 1990).

Cooper et al. (1984) evaluated the specific cause of 1089 anesthesia-related incidents in four U.S. hospitals. Anesthetists, anesthesia residents and nurse anesthetists were interviewed about their experience with anesthesia-related incidents. The results showed that 4% of reported critical incidents involved equipment failure such as a disconnected breathing circuit or false alarms in the monitor. Human error seemed to be a more important factor involved in the reported incidents; the proportion of anesthetic-related incidents due to human error was found to be over 60 percent (Cooper et al. 1978; Cooper et al. 1984; DeAnda & Gaba, 1989).

Arbous et al. (2001) showed that in 12% of all anesthesia-related incidents, with death as a result, inadequate patient monitoring was an important factor. Cooper et al. (1984) showed that anesthetists' failing to check the monitor was a factor in 32% of the incidents and inattention or carelessness were a factor in 19% of incidents. In incidents with substantial negative outcomes (i.e. death, cardiac arrest, prolonged stay in hospital etc.), problems with vigilance (i.e. sustained attention, see chapter 3.2.3.) or monitoring were a factor in 16% of the cases.

The occurrence of anesthesia-related incidents due to human error led to studies focusing on the factors responsible for decrease in anesthetist's performance. Cook et al. (1991) reported anesthesia-related incidents and linked these incidents with cognitive processes in anesthetists. In an extensive case study, Cook et al. (1991) observed 57 incidents over a 2-year period and found strong relations between incidents and processes such as situation awareness and decision making (as discussed in next paragraph) described in cognitive psychology. They argued that future research for anesthesia-related incidents should aim at describing cognitive processes in the anesthetist to reduce human error in practice.

In this chapter we presented research that focused on recognizing the factors that play a role in the occurrence of anesthesia-related incidents. Several studies showed that a high number of incidents were due to human error in monitoring patient variables (Cooper et al. 1978; Cooper et al. 1984; Arbous et al. 2001; DeAnda & Gaba, 1989). They found that performance of patient monitoring is not always optimal during surgery; anesthetists miss important cues because of an incomplete scanning of the monitor or decrease in attention to the monitor (Cooper et al. 1984). Further investigation of these human errors is presented in the next chapter. To gain insight into these errors we gained information in the field of human cognition and linked research on cognitive models to the practice of anesthesia.

3.2. Cognitive processes in the anesthetist

The operating room is a very complex environment (Gaba et al. 1987). Anesthetists are occupied with perceiving patient information, staying alert for adverse events in patient health, remembering occurrence of earlier events, adjusting diagnoses based on new patient information, decision making, communicating with other personnel and performing actions to satisfy medication goals (Weinger & Slagle, 2002). In order to reduce the occurrence of human error in anesthesia, several studies were conducted to investigate the role of cognitive processes on anesthetists' performance in anesthesia practice (DeAnda & Gaba, 1991; Gaba, 1995; Kremer et al. 2002). In Psychology studies, many of these cognitive processes have been extensively investigated and general theories are proposed to provide more insight into their interactions (Tversky & Kahneman, 1974; Endsley, 1988; Wickens, 2004). In this chapter, we focus on the cognitive processes in the anesthetist that influence anesthetist' monitoring performance. We start this chapter by discussing the role of decision making in the anesthetists' tasks. Next, we discuss situation awareness: a cognitive model that is extensively studied in the field of aviation. Finally, we will discuss vigilance (i.e. sustained attention); a state that is specially required in the anesthetist's job.

3.2.1. Decision making

Decision making is a crucial process in the anesthetist's tasks. During surgery, the anesthetist has to decide what goals must be accomplished and what actions should be executed to reach these goals (Gaba et al. 1995). In a changing environment, the anesthetist has to hypothesize the expected outcome for the patient's health based on the obtained information. We discussed earlier the influence of human error on the occurrence of anesthesia-related incidents during surgery. Cooper et al. (1984) reported that 33% of all human errors in anesthesia-related incidents with substantial negative outcomes (i.e. mortality, cardiac arrest, suspended stay in the hospital) are due to judgmental errors in the anesthetist. They concluded that these poor judgmental errors, such as administering an overdose of drugs, arise from insufficient training or poorly developed decision making skills (Cooper et al. 1984). DeAnda & Gaba (1991) tried to obtain more detailed information about the process of decision making in anesthetists by using a speak-aloud protocol during simulated incidents. They studied cognitive models proposed in Psychology studies (Wickens et al. 2004, Tversky & Kahneman, 1974, Endsley, 1988) to gain more understanding in the cognitive processes that play a role in anesthetist decision making.

Wickens et al. (2004) defined three stages in the decision making process: Cue reception and integration, hypothesis generation and selection, and generation of plans and choice for actions. In the first stage, a number of information cues perceived from the environment go into working memory. The cues must be attended and interpreted for the next stage. In the second state the cues are used to generate one or several hypotheses. The hypotheses are brought into working memory and matched with the cues. When a matching hypothesis is found, one or more alternative actions are generated and finally one or more actions are chosen from the set of alternative actions. These stages are constrained by mental resources such as working memory and long-term memory capacity (Wickens, 2004). For instance, in a high workload environment, the practitioner must divide his/her attention between several sources (Craig, 1991). These constraints lead to an incomplete mental image of the environment (Gaba et al. 1989). This can have adverse effects on decision making and can potentially lead to incorrect diagnoses (Kremer et al. 2002).

Biases and heuristics in decision making

Several studies showed that humans use biases and heuristics in the process of decision making. Heuristics are easy ways of making decisions that can be represented as rules-of-thumb (Tversky & Kahneman, 1974). The use of heuristics in the decision process is very efficient but does not always guarantee the best solution (Wickens et al. 2004). Biases are the result of the use of heuristics in decision making: reasoning with incomplete information can lead to a biased or simplified mental image. Biases and heuristics can occur in all three stages of the decision process we mentioned earlier. *Cue primacy* is an example of a heuristic known to occur in the first process of decision making (i.e. receiving and using cues). With cue primacy, the practitioner tends to assign more weight to the first few cues in the total number of cues perceived over a period of time (Tversky & Kahneman, 1974). The resulting bias can lead to "anchoring" on hypotheses that are primarily based on the cues that were received first. Extensive research on decision making of nurse anesthetists recognized the use of several biases and heuristics in decision making (Kremer et al. 2002). For anesthetists, using the anchoring bias can result in another heuristic called *cognitive tunneling*, when an early diagnosis is adopted and contradictory evidence is ignored (Kremer et al. 2002). Another heuristic that can be found in anesthetists' reasoning is the *availability heuristic*. Anesthetists use this heuristic to estimate probabilities for the occurrence of specific instances during surgery. For example, an anesthetist chooses the hypothesis that first comes to mind. The availability of hypotheses in memory depends on the frequency and recency of occurrence of situations where these hypotheses were the correct diagnosis (Tversky & Kahneman, 1974; Kremer et al. 2002; Wickens et al. 2004). A common heuristic used by anesthetist nurses is the *representativeness heuristic* (Kremer et al. 2002). With this heuristic, the observed pattern in the perceived cues is compared to a prototypical example of this situation (Tversky & Kahneman, 1974). An example of the representativeness heuristic in anesthesia practice is judging whether shortness of breath originates from cardiac arrest or pulmonary failure (Kremer et al. 2002). The representativeness heuristic can result in a bias when a perceived situation is different from the prototypical example even though a part of the pattern of cues is similar (Wickens, 2004).

3.2.2. Situation awareness

Humans use heuristics to make decisions when their informational resources are incomplete (Tversky & Kahneman, 1974). To decrease the chance of biases that lead to erroneous decisions, anesthetists must obtain fundamental information from the patient situation. In other fields such as aviation, the decision making process of pilots is extensively studied. Endsley (1988) studied the factors that are of influence on the decision making process in pilots. She found that situation awareness was an important precondition for decision making. In this paragraph we will discuss the importance of situation awareness in the decision making process of anesthetists. We compare the field of aviation with anesthesiology, since both fields share common characteristics. Other than in anesthesiology, situation awareness is extensively studied in aviation research.

As in anesthesiology, most critical accidents that occur in aviation are due to human factors (Cooper et al. 1978; Cooper et al. 1984; DeAnda & Gaba, 1989). Research in the aviation field aims to reduce human error by focusing on cognitive processes such as situation awareness and decision making. Endsley (1988) defines situation awareness in aviation as "the pilot's internal model of the world around him at any point in time". More general, situation awareness is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1995). In today's aircrafts, electronic systems sense the environment and provide the pilot with this information. Pilots are constantly monitoring multiple sources inside and outside their cockpit while they perform a sequence of tasks to maneuver the aircraft through the environment (Sarter & Woods, 1991). Safe operation of the aircraft consistent with the pilot's goals depends on the assessment of the changing situation, perceiving and interpreting operational parameters from the aircraft, processing navigational information and keeping track of external factors such as other aircrafts (Endsley, 1995). Situation awareness plays a crucial role in the process of decision making; inaccurate situation awareness in the most experienced pilot can lead to making the wrong decisions during flight (Endsley, 1988; Endsley, 1995).

Anesthesiology shares many characteristics with aviation. Common factors in both fields are a dynamical environment, complex tasks with high information load, variable workload and high risk for accidents (Sarter & Woods, 1991; Gaba et al. 1995). Gaba et al. (1989) studied the shared characteristics between aviation and anesthesiology in depth: firstly, anesthetists and pilots must detect cues that present a changing situation by keeping track of a variety of data-streams, secondly, anesthetists and pilots have to adapt to an evolving situation and predict future states of the environment and thirdly, both anesthetists and pilots have to keep track of and utilize special elements of knowledge (i.e. characteristics about the patient or case for the anesthetist and characteristics about the mission for the pilot). The operating theatre is a challenging and dynamical environment in which the health status of the patient can fluctuate under influence of the surgery process. The anesthetist acquires the progress of the administered anesthetic in the patient (Weinger & Englund, 1990) by watching multiple data sources and keeping track of trends. Sources that provide the anesthetist with vital information about the process are the patient's responses to the operation, information from the patient monitors, auditive alarms and communication with other operation room personnel (McDonald et al. 1990).

To reduce human errors in complex tasks, several studies proposed models for describing cognitive processes and interactions that are responsible for fluctuations in situation awareness (Wickens, 1984; Wickens, 2002; Endsley, 1988; Sarter & Woods, 1991). Endsley (1988) divides situation awareness into three levels: perception of the elements (objects and events) in the environment, comprehension of the meaning of the specific elements and projection of the future state of these elements. In Endsley's (1995) model of problem solving in aviation (see Fig. 7), she makes a clear distinction between situation awareness, the process of decision making and action performance. From Endsley's model follows that situation awareness has a direct influence on decision making. The perception and comprehension of the environmental elements and prediction of future states of those elements allow the pilot to make a decision and perform the action appropriate for the specific situation. Situation awareness is influenced by individual factors and system factors. Individual factors are goals and objectives for task performance and preconceptions about the environment. More inter-personal individual influences on situational awareness are factors such as courage to take risks or experience of the pilot on the task. Other influences on situation awareness are attention, working memory (Wickens, 1984), workload, and stress (Endsley, 1995).

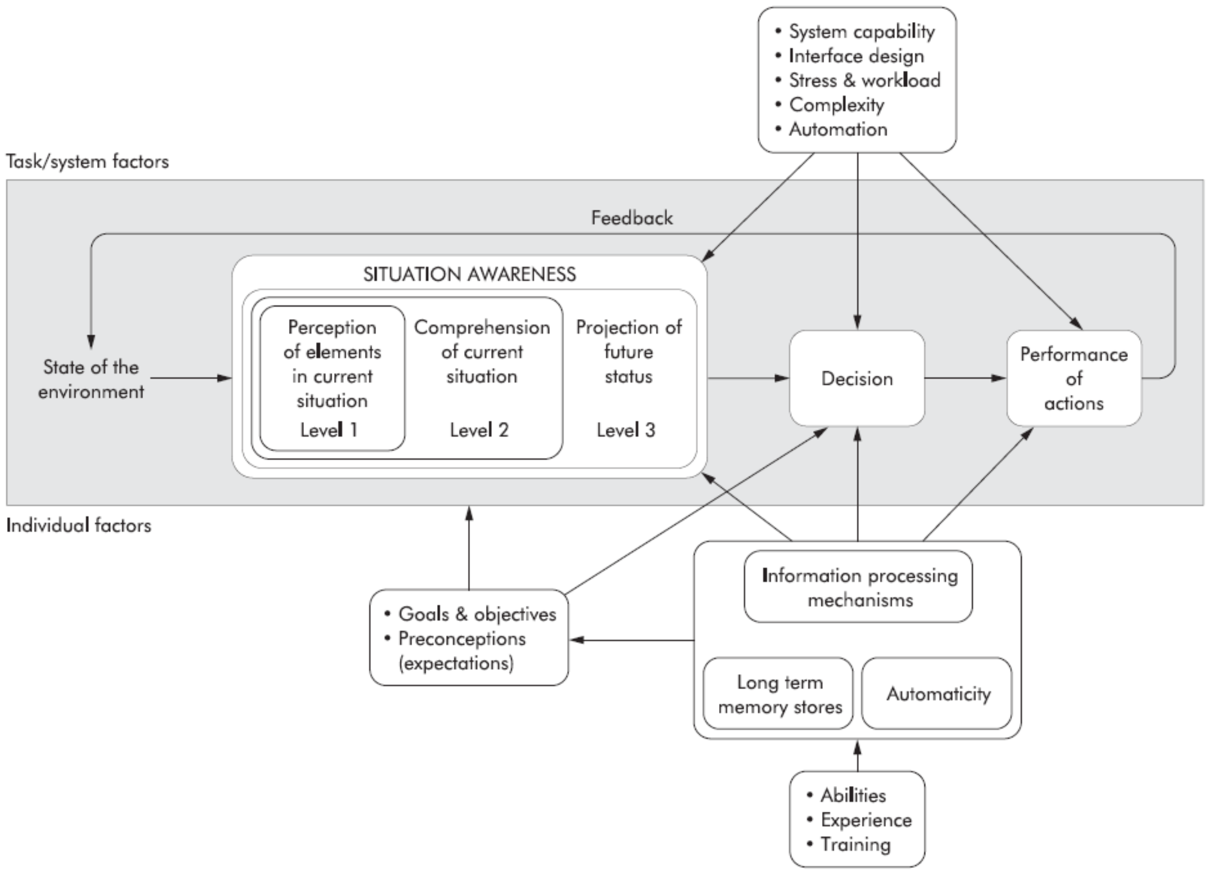

Figure 7. Model of situation awareness and interaction with other cognitive processes in aviation (Endsley, 1995).

The above mentioned construct of situation awareness is thought to be an integral part of the anesthetist's problem solving behavior (Gaba et al. 1989). Gaba et al. (1989) proposed a model of the cognitive processes in anesthetists based on existing models in aviation (see Fig. 8) and cognitive psychology (Rasmussen & Lind, 1982). This model depicts the assumed processes for situation awareness and decision making in anesthetists. Gaba et al. (1989) constructed the model with the notion from Reason (1987) that anesthetists' decisions are mostly made with *limited rationality,* referring to incomplete information from a multitude of sources competing for attention.

The model in Figure 8 identifies five levels of abstraction in the anesthetists problem solving behavior: sensory/motor level, procedural level, abstract level, resource management and supervisory control level, whereas the latter two levels are assumed to be responsible for situation awareness (Gaba et al. 1995). The first element concerning situation awareness is the observation of the different data streams by monitoring and cross checking the patient. The next element depicts verifying the occurrence of artifacts in the observed data; anesthetists reason whether the observed data is useful for further processing or whether they have to make other observations. After verification, the data is processed to check whether the data is considered a problem in patient health. Attention to these processes must be allocated and can compete with attention for other processes such as motor-actions. In order to divide his/her attention between several data streams and processes, the anesthetist has to decide which process gets priority for allocating attention towards, based on current knowledge about the situation (Gaba et al. 1989, Gaba et al. 1995).

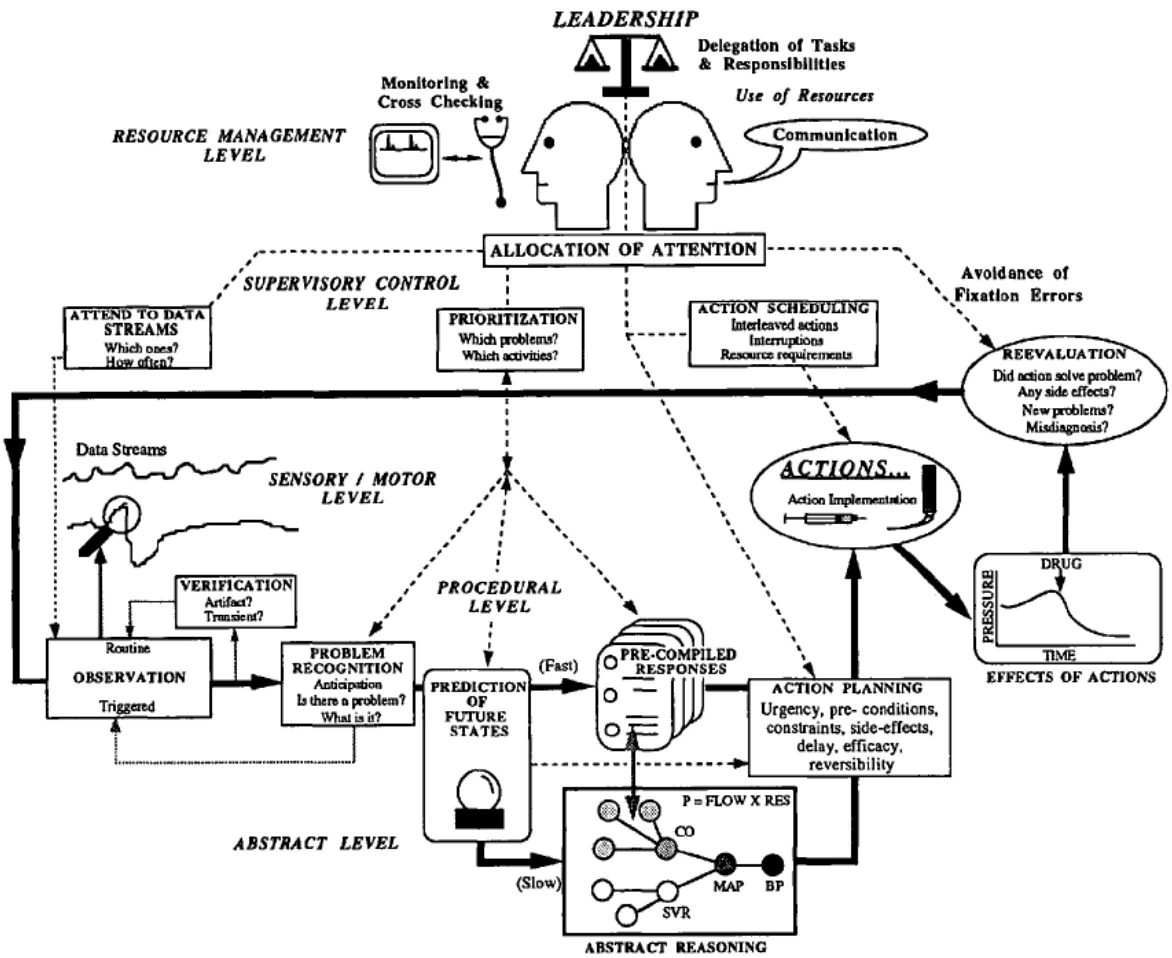

Figure 8. A cognitive process model of the anesthesiologist's problem-solving behavior (Gaba et al. 1995).

Errors that occur in the process of situation awareness can lead to prioritization of the wrong information. Consequently, the decision making process is based on incomplete or incorrect information. Gaba et al. (1995) present an example where errors in the situation awareness lead to disastrous results for the patient: "a patient was having surgery on her eye under general anesthesia. After inducement of anesthesia and the insertion of a breathing tube in the patient, the operating table was turned 180 degrees to give the surgeons better access to the surgical field. This maneuver requires several hoses and wires from the anesthesia equipment to be disconnected and reconnected to the patient. After moving the table, the anesthesiologist verified that the breathing tube was still correctly placed and that the patient's arms were properly padded to protect them from the mechanical compression. Because of the increased workload of these activities, he failed to recognize that the patient's heart rate was critically slow and that the blood pressure could not be detected by the blood pressure measurement system".

Measuring situation awareness in anesthetists is crucial to recognize the bottlenecks in anesthetist performance that could lead to adverse effects in patient safety. Wright et al. (2004) suggested the use of human patient simulators to study situation awareness in anesthetists. A human patient simulator (see Fig. 9) is a mannequin that replaces a real patient in the operating room and allows the anesthetist to perform many clinical maneuvers. The artificial patient is controlled by a computer and is capable of showing most of the physiological responses that can be found in a real patient. As in a real life situation, the patient simulator is connected to a patient monitor. Patient's responses are simulated by using complex scripts that are constructed based on physiologic and pharmacologic models of real patients (Gaba et al. 1995). Patient simulators are utilized for both practice and research; anesthetists can safely practice their skills on these simulators without harming any patient. Researchers utilize patient simulators to study anesthetists' behavior in stressing situations.

DeAnda & Gaba (1991) studied the influence of experience on the detection speed for unplanned incidents in a human patient simulator. Anesthetists with different levels of experience were asked to speak aloud about their reasoning during the simulation of a surgery. The experimenters were able to simulate unplanned incidents such as endobronchial intubation (i.e. tube is placed in bronchia instead of in the trachea), occlusion of the intravenous line (i.e. intravenous medication is blocked) and cardiac arrest.

Figure 9. Human Patient Simulator

In the current study, we recognize the need of obtaining an optimal situation awareness for the anesthetist as a solid basis for the decision making process. We focus on the monitoring of patient variables to construct situation awareness for the current patient's health status. Errors in situation awareness that lead to anesthesia-related incidents are often due to inattention towards patient monitors (Cooper, 1978; Cooper, 1984). Inattention towards the patient monitors can occur in periods of high workload as well as periods of low workload (Weinger & Englund, 1990). High workload situations require the anesthetist to divide attention between several time consuming activities (e.g. motorical actions and a multitude of visual cues). In low workload situations the anesthetist is less aroused because the patient's health remains stable for a longer period of time (Weinger & Slagle, 2002). In the next paragraph we will discuss the role of vigilance in anesthetists' monitoring behaviour.

3.2.3. Sustained attention (vigilance)

Vigilance is a subset of situation awareness and depends on alertness, attention and diagnostic skills during periods of low-workload (Weinger & Slagle, 2002). Vigilance tasks are one of the most difficult tasks for humans, because it requires a state of alertness at all times (Mackworth, N.H., 1956; Mackworth, J.F., 1968, Gluckman et al, 1993). Mackworth (1956) defines vigilance as "*a readiness to detect and respond to certain specified small changes in the environment, occurring at irregular time intervals"*.

Examples of contexts that require vigilance are building security, military watch keeping, air traffic control or monitoring of industrial processes such as in power plants. The common denominator in these contexts is the high cost of detection failure (Craig, 1991); the worker must be alert for changes in an environment with low-level activity. These changes in the situation require a swift and precise response during a state of emergency. Mackworth (1948) studied decrements in vigilance. He studied vigilance in radar and sonar operators during World War II. His experiments sought to determine the reason why these radar and sonar operators missed weak signals on their monitors signifying the presence of enemy submarines. Mackworth (1948) performed the Clock test, which was an experiment where subjects were presented with a clock that consisted of one pointer. The pointer moved with small steps of identical length in the same direction during the experiment. Subjects watched the clock for a period of 2 hours and responded when they noticed that the pointer moved twice the normal step distance. The pointer did so only 12 times in 20 minutes. In his study Mackworth (1948) showed that the accuracy of detections in subjects declines by 15% after 30 minutes of watching the clock. After these first 30 minutes, the accuracy of detection declines more gradually. Mackworth showed a decrement of vigilance (or sustained attention) for small visual cues over time.

The job of the anesthetist is an example of a vigilance task, complications can evolve from small physical responses into a more intricate situation where the original cause is eventually hard to diagnose (Gaba et al. 1987; Rowbotham & Smith, 2006). Thus, the anesthetist must stay alert for very small changes in patient variables (Weinger & Englund, 1990; Loeb, 1994). A number of factors can potentially cause a decrease in vigilance in anesthetists (Weinger & Englund, 1990). The typical operation room is filled with noise that could have a negative effect on the anesthetist's vigilance (Miles et al. 1984); anesthesia equipment produces beeping noises and alarms that can drive the anesthetist's attention away from the monitors. Surgical equipment can also be very noisy, for example:

drills or fluid-suction devices produce measured sound levels of 108 dB (Hodge & Thompson, 1990). Other influences that can lead to a decrease in vigilance and performance in the operation room are the combination of high temperature and low humidity: conditions that are required in the surgery of burn patients and neonates. High temperature can lead to fatigue and low humidity can lead to dehydration in the anesthetist (Weinger & Englund, 1990). The presence of environmental toxicity, ambient lightning and inflexibility of the workspace can also lead to a decrease in concentration in the anesthetist (Weinger & Englund,1990).

During the “silent” periods in a surgery, some anesthetists divert their attention away from the patient to other non-patient activities. Examples of these activities are conversing with colleagues or reading medical records. Slagle & Weinger (2009) showed that 35% of anesthetists read medical literature at some time during these low-workload periods. Slagle & Weinger (2009) evaluated the influence of intraoperative reading on the vigilance of anesthetists and showed that reading during the procedure did not lead to slower responses in identifying a random illumination of the monitor. They concluded that reading during surgery did not lead to a decrease in anesthetist vigilance. McDonald et al (1990) studied anesthetists’ activities during surgery. They found that anesthetists spent 14.3% of the time on indirect monitoring (i.e. viewing patient monitors) and 44.8% on direct monitoring of the patient. Loeb (1994) showed that anesthesia residents scanned the monitors more briefly during induction than they did during surgery, because during induction, anesthesia residents were occupied with a high number of activities. Loeb (1994) found a decrease in attention causing a decrease in recognition of anomalies in patient health during induction compared to attention during surgery. Warm et al. (2008) found that vigilance also causes an increase in workload.

There are several technical devices that help anesthetists in attending toward anomalies in the patient’s health or making decisions about the patient. In the next paragraph we will discuss these devices in detail.

3.3. Technical support for anesthetists

3.3.1. Alarms and Auditory displays

To avoid critical incidents, the anesthetist looks for anomalies in patient variables during surgery. Variables that deviate from a steady-state could indicate the occurrence of a complication in the patient and must be treated accordingly. To increase saliency of the variables that exceed a certain preset threshold, current patient monitors are equipped with audible alarms. These alarms warn the anesthetist when a variable reaches an abnormal value, for instance when heart rate drops to values below 40 beats per minute. The anesthetist determines the appropriate thresholds for all variables. Whenever a threshold is exceeded, the alarm exerts a beeping noise that will keep ringing until the anesthetist responds to it. The anesthetist can choose to execute an action that influences the patient’s health status in order to get the abnormal variable value back to a steady-state. Sometimes anesthetists kill the alarm by lowering the alarm audio volume or by shutting the alarm off (McIntyre, 1985; Block et al, 1999). Watson et al. (2000) showed that anesthetists actively respond to 3.4% of all audible alarms. 5.3% of all alarms led to a response on first sounding and 1.9% of all alarms led to a response at re-run of the sound. There are a number of reasons why anesthetists choose to kill an alarm, reduce the volume or even shut off an alarm completely. The most common are: need for quietness in the Operation Room and reducing the number of false alarms (McIntyre, 1985).

False alarms can originate from failure in measure equipment, for example, moving the patient in another position can disconnect the pulse oxymeter from the patient's thumb. False alarms can also be caused by pre-set alarm limits. Anesthetists have to consider the margin of their alarm limits for each variable: a high margin results in fewer false alarms, but increase the risk of missing complications. Smaller margins result in more false alarms, but an increased chance to recognize complications in time (Block et al. 1999).

To increase the usefulness of alarms, Ballast (1992) presented an alarm system that responded to unwanted changes in the variable's value over a chosen time-period. Since these changing values stay within the normal range, they often go unnoticed in the scanning behavior of the anesthetist (Weinger & Englund, 1990). The type of warning system proposed by Ballast (1992) could be valuable for an anesthetist during surgery to alleviate this change blindness. Although audible alarms can be helpful in recognizing complications, Ballast (1992) suggested that visual signals would be more suitable in the operating theatre, since audible false alarms are perceived as annoying and distracting.

In auditory displays, each physiological response has its own continuous sound and rhythm (Jones & Kirk, 1970; Seagull et al. 2001; Sanderson et al. 2005). For instance, the auditory display for heart rate beeps at each pulsation of the heart and also the frequency of this sound changes according to the Oxygen concentration measured by a pulse oxymeter. A high saturation produces a high-pitched tone, while a low saturation produces a low-pitched tone. An auditory display provides the anesthetist with the same information that can be found on a visual display, so the anesthetist does not have to keep track of the monitors all the time. Auditory displays reduce visual workload for the anesthetist by representing the values for a variable as an auditory signal (Seagull et al. 2001).

Sanderson et al. (2004) studied the effectiveness of auditory displays on patient monitoring in non-anesthetist subjects. During a simulated surgery, Sanderson et al. (2004) observed the patient monitoring behavior of the subjects during a patient simulation. All patient variables were both visible on the monitor and sonified as an auditory display. Subjects were asked about the patient's status during the experiment. They found that subjects' attention towards the patient monitors decreased when presented with full sonification of patient variables. The speed of providing the patient's status to the experimenter increased in the condition with only sonification. Accuracy for patient status increased when subjects had the opportunity to view the patient variables and accuracy performance was worst in the condition with sonification alone. This research shows that with only sonification of patient variables, the practitioner obtains a patient overview in a faster, but less accurate fashion than when also viewing a patient monitor.

3.3.2. Decision Support Systems

In the current operating room, machines are able to support the anesthetist by performing tasks that require the acquisition of information or the execution of actions. For instance, various measuring devices acquire information about the patient's physical responses and infusion pumps automatically provide the patient with a preset dose of anesthetics. In the last paragraph we presented auditory systems that provide automation of a higher order (Parasuraman et al. 2000). Auditory systems compare patient information with preset margins and warn the anesthetist when a variable exceeds the threshold. This type of automation can be considered as analysis automation (Parasuraman et al. 2000); patient information is analyzed by comparing it to the threshold. A higher level of automation is decision selection, whereby the machine interprets more than one variable and infers the most probable outcome based on prior knowledge of the case. Systems that are capable of that kind of automation are called Decision Support Systems (DSS).

The aim of DSSs is to support humans in the performance of decision making tasks and choice of appropriate actions. A Decision Support System provides the anesthetist with a number of diagnoses (Renardel de Lavalette et al, 1997, Becker et al, 1997, Lowe et al, 2000) based on a combination of measured patient variables. The DSS calculates the probability of the occurrence of a certain anesthesia-related complication by comparing combinations of measured patient variables to medical knowledge of anesthesia complications. Kizito (2006) implemented a DSS for anesthetists. In his system, the five most probable diagnoses were displayed to the anesthetist. These diagnoses were based on a combination of abnormal values of patient variables. Although the problem space for possible diagnoses is finite, the formalization of logical rules appeared to be very difficult. Among anesthetists, there is no consensus onto what combination of patient variables indisputably leads to a specific diagnosis. Another difficulty is that a DSS has no knowledge about external events, such as surgical activity during the operation. This makes DSSs thus far not usable in the operating room.

3.3.3. Monitor improvements

During World War II a large number of accidents in aviation were attributed to human error. From those findings, the field of human factors arose. The goal of studies on human factors is to take human limitations into account when optimizing equipment design (Botney & Gaba, 1990). This makes that equipment is easier to use. In the operation room, the anesthetist is constantly interacting with monitors and other equipment; human factors play a major role in the anesthetist's job. It is critical that anesthetists can easily interact with their monitoring equipment and gain information with minimal increase of mental workload. Monitors should assist anesthetists in performing their task safely and efficiently. This can be obtained by displaying the needed patient information in such a way that it is easily processed by the anesthetist.

Visualizations of patient variables

Instead of introducing an intricate system such as a DSS, attempts have been made to change the visualization of patient variables in anesthesia monitors. Tappan et al. (2009) presented an experimental interface, where changes of physiological variables were displayed visually (see Fig. 10). When a physiological variable shows a slow upward or downward trend, the monitor warns the anesthetist with a visual cue (i.e. colored triangle). Subjects were presented with scenarios where a complication would occur. The display of visual cues resulted in a reduction of mean recognition time of complications.

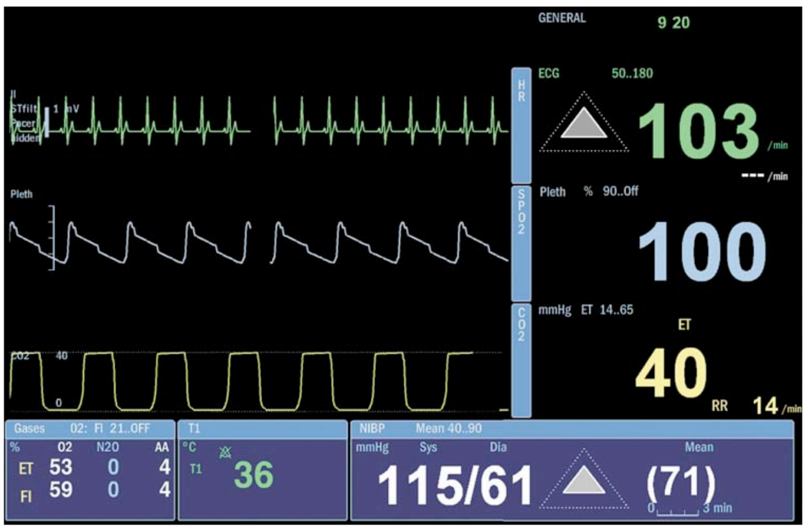

Figure 10. Anesthesia monitor with visual alarm (Tappan, 2009)

To ensure fast detection of anesthesia-related complications, anesthetists' vigilance should be optimal (Weinger & Englund, 1990). A better visual representation might help the anesthetist to detect and identify complications faster. Visualizations of variables can lead to an improved overview of variable configurations. Anesthetists must consider the relationships of the different variables to create an image of the patient's health status. In this type of monitoring tasks, the use of a configural display can help the user in obtaining a quick overview of the situation (Wickens et al. 2004). An example of a configural display was studied by Woods et al. (1981). They developed a display for the nuclear power plant control room (see Fig. 11). This display showed all safety variables as parts of an octagon. A deviation of a variable from its normal value caused a disturbance of symmetry in the octagon (see Fig. 11). This visualization provides the viewer with an added *emergent* feature: symmetry (Wickens et al. 2004). This feature helps the user to make use of pattern recognition, which is a highly developed capability in humans (Bennet & Flach, 1992).

Several interfaces were presented in earlier research, some aimed at supporting human pattern recognition (Michels et al, 1997, Blike et al, 1999), as part of a DSS (Lowe et al, 2001) or as a graphical visualization for a specific system in the body (Drews et al. 2001, Wachter et al. 2003, Albert et al. 2007). Latter research focuses on graphical representation of patient variables in the cardiovascular and pulmonary system.

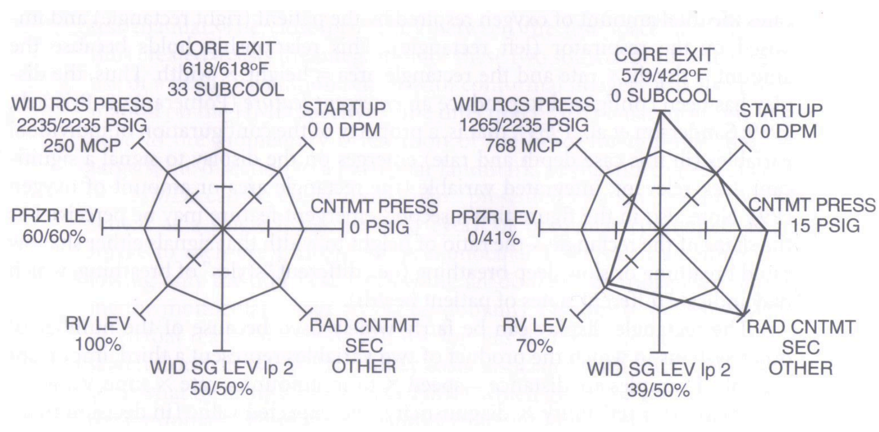

Figure 11. Octagon display (Woods et al. 1981)

Metaphorical interface design

Blike et al. (1999) built an interface for anesthetists based on metaphorical objects. Metaphors are graphical representations for concepts existing in the real world. Cole & Stewart (1993) presented a metaphor for patient variables in an anesthesia monitor. They explained that the traditional visualization of variables in a line graph is more suitable than a table of values of the same data, but has many disadvantages in providing a quick overview of the situation. The visualization of different variables in the same space presented as line graphs makes the display very cluttered. Cole & Stewart (1993) presented a rectangular metaphor for visualization of respiratory data (Fig. 12). The width of a rectangle represents the average respiratory rate. The height of a rectangle presents the tidal volume, this is a metaphor for the changes in air-volume in the lungs during each breath. Inside the rectangle the amount of FiO_2 gas is presented as a gray area and the dead space between breaths (i.e. the part of the tidal volume that stays in the airways and does not contribute to effective ventilation of the lung) is presented as a white area. This simple metaphor was expected to support quick pattern recognition and early detection of anomalies in variable values.

Michels et al. (1997) implemented the rectangular metaphor in an extensive anesthesia interface called the Integrated Graphic Anesthesia Display (IGAD). 30 different variables were presented in a single display (Fig. 13). An arrangement of variables for each organ system (respiratory, cardiovascular, arterial, etc.) was displayed. The steady-state values for each variable were presented as the frame of each rectangle, thus the colored area could “flow over” the boundaries of a rectangle. In the interface of Michels et al. (1997), all variables are presented in a consistent manner. This makes pattern recognition easier for the anesthetist. A simulation where anesthetists were subjected to 4 critical events (i.e. blood loss, inadequate paralysis with spontaneous ventilation, cuff leak and depletion of soda lime) showed a significant effect in identification and detection time of these events. Subjects detected 2 of 4 critical events twice as fast in the metaphorical interface compared to a normal anesthesia monitoring setup. For 3 of 4 critical events the cause of the event was identified faster with the metaphorical interface compared to a normal anesthesia monitoring setup.

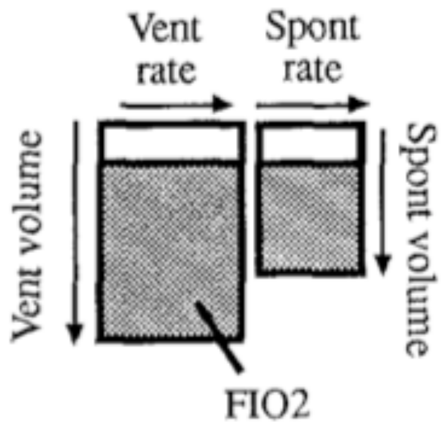

Figure 12. Metaphorical idea from Cole & Stewart (1993)

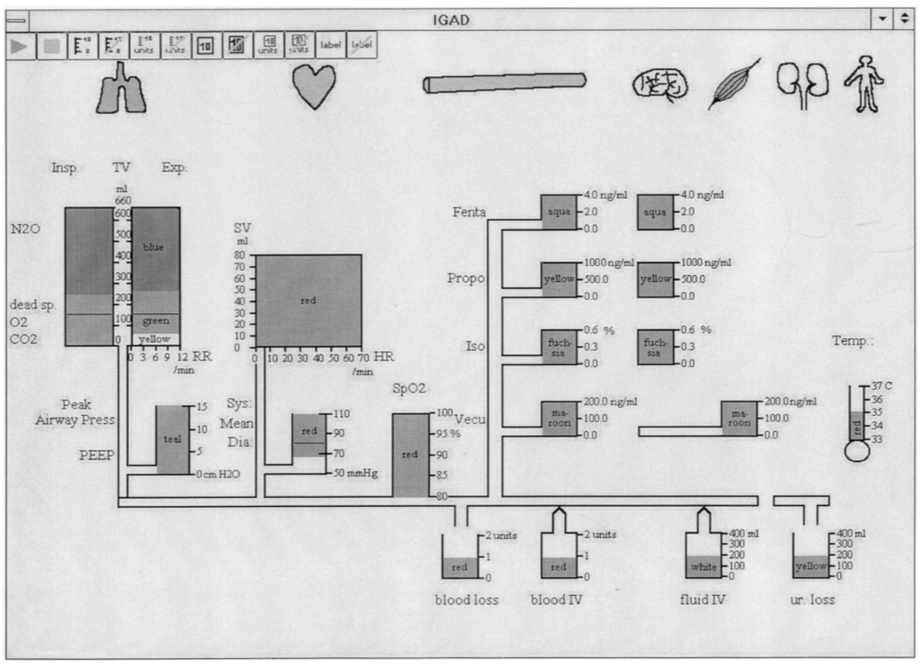

Figure 13. Original IGAD display from Michels et al. (1997)

Chapter 4. Current study

In the current study we built and tested two new metaphorical anesthesia monitors. From earlier research follows that improving recognition performance by presenting simple metaphors is an interesting alternative for the usual monitoring setup. Humans are very skilled in pattern recognition; therefore, an advanced visual interface could help in faster recognition of complications. In existing publications for testing a metaphorical interface during a simulated surgery, Michels et al. (1997) found a positive influence on task-performance of anesthetists on recognition of relative simple complications. We will investigate whether these results can be replicated with our new metaphorical monitors. We hypothesize that anesthetists and anesthesia residents will recognize complications faster with the new metaphorical monitors compared to the traditional patient monitor.

During surgery, anesthetists normally keep track of trend information in patient variables (Ballast, 1992; Gaba et al. 1995; Byrne et al. 1998). This trend information was not visualized in the metaphorical monitors as proposed by Michels et al. (1997). Tappan et al. (2009) showed that increased saliency of variables due to changing values, drives anesthetists' attention towards these values. Ballast (1992) recommended the use of visual trend information as a possible alternative for auditory alarms. Based on these recommendations we hypothesize that anesthetists and anesthesia residents will recognize the complications faster in monitors with trend information compared to the monitors without trend information. Consequently, we decided to construct a metaphorical monitor where trend information is presented by arrows.

We also constructed a monitor with both metaphorical and traditional information presentation. This redundant monitor displays the same patient information in two different visualizations. In psychology, the so-called *redundancy gain* has been studied extensively. This effect indicates a faster recognition time in the presentation of two identical target stimuli than in the presentation of a single target stimulus (Miller et al. 1982; Wickens et al. 2004). Based on this effect, we hypothesize that anesthetists and anesthesia residents will recognize the complications faster in redundant monitors compared to single monitors.

In chapter 5, we present the pilot study resulting in design considerations for the new metaphorical monitors. In chapter 6 we discuss the development of these metaphorical monitors. The monitoring experiment is presented in chapter 7-9.

Chapter 5. Pilot

Various studies have showed the positive effects of different visualizations of patient variables on monitoring performance in anesthetists (Michels et al. 1997; Tappan et al. 2009). They compared alternative monitors to current numerical and curve-based anesthesia monitors. Michels et al. (1997) constructed the IGAD metaphorical monitor (Fig. 13) and found that anesthetists detected and identified complications faster with this monitor compared to traditional monitors. In the current study, our goal is to test whether an improved IGAD monitor leads to similar results as was found by Michels et al (1997). Michels et al. (1997) did not provide design considerations of the IGAD in their paper, thus we suppose that the IGAD monitor was not presented to anesthetists for feedback on the design. We chose to develop a new metaphorical monitor that is based on the metaphorical idea of Michels et al. (1997) combined with the results from a pilot research. Next, we present this pilot research in which we interviewed anesthetists about their design ideas for a new metaphorical monitor.

5.1. Interviews

We interviewed a group of anesthesiologists, anesthesia residents and nurse anesthetists about their needs and design preferences for a metaphorical monitor. These practitioners are all familiar with patient monitoring and administering anesthesia. Five anesthetists, five anesthesia residents and five nurse anesthetists from the UMCG were interviewed (See Appendix A for questionnaire). Beforehand, subjects were asked what patient information they would prefer in a monitor in order to create a solid diagnosis for the patient's health status during surgery. In each interview we presented a set of eight alternative metaphorical monitors (See Appendix B) to provide the subjects with an overview of the possible visualizations. The presentation of 8 metaphorical monitors started with the IGAD monitor from Michels et al. (1997) and the following presentations showed variations in presentation of variables, coloration of variables, combinations of variables, numerical axes, positions of numerical values, background colorations, steady-state frame colorations, positions of icons and presentations of trend information.

5.2. Results

Pilot results showed that there was consensus on four variables that anesthetists, anesthesia residents and nurse anesthetists require to create a solid diagnosis of the patient's health status during surgery. These variables were expired CO_2, peak pressure (PAW), oxygen saturation (SPO_2) and blood pressure. The frequency of answers for the other variables is shown in table 1. The IGAD monitor from Michels et al. (1997) showed the levels of administered anesthetics (Isoflurane, Propofol, Fentanyl and Vecuronium) and fluids (blood loss, urine loss, application of blood intravenously and application of fluids intravenously). Our pilot results show no consensus on the requirement of presenting administered anesthetics and fluids in our metaphorical monitor.

In the pilot, we presented subjects with several alternatives for the position of variables. The results show no consensus between subjects in the need to present inspired O_2 stacked with expired CO_2. 10 out of 15 subjects (66.7%) preferred the presentation of heart rate stacked with blood pressure.

Table 1. Importance for presentation of variables based on questionnaire in pilot research: the number of anesthetists/anesthesia residents/nurse anesthetists who indicated that a particular patient variable is required for creating a solid diagnose of patient's health status.

patient variable	**# subjects**
Expired CO_2	15
PAW	15
SPO_2	15
Blood pressure	15
Inspired O_2	14
PEEP	14
Heart rate	14
Temperature	13
Tidal volume	12
Expired CO_2	11
Inspired O_2	11
Respiratory rate	8
BIS	8
Isoflurane	7
Propofol	6
Fentanyl	4
Vecuronium	4
Respiratory minute vol.	4
Blood loss	3
Blood Intravenous	2
Fluids Intravenous	2
Urine loss	2

There appears to be a lot variance in the subjects' answers on preferred colors for rectangle surfaces of variables. We decided to assign the vital patient variables with colors that were chosen by the majority of subjects (See table 2). Subjects were also asked whether they would prefer the presentation of trend information. 13 of 15 subjects (86.6%) indicated that the monitor should present information about the speed of trend change in patient variables. We presented subjects with multiple visualizations of trend information in 2 dimensions: speed and direction. We chose to visualize the direction of the trend with an upward or downward pointing arrow representing respectively incline and decline of a patient variable. Different alternatives for the presentation of trend speed were proposed: trend speed is proportional with number of arrows, length of arrows or thickness of arrows. Results show that most subjects preferred a representation of trend speed by thickness of the arrow (See table 3). Subjects indicated that trend information in the cardio-vascular system was thought to be more useful than in the respiratory system, because changes in the respiratory system are often due to anesthetists' own actions on the ventilator machine (e.g. 100% Oxygen during induction).

Table 2. Selected colors for the vital patient variables based on the questionnaire

patient variable	color
Expired CO_2	white
SPO_2	yellow
Blood pressure	red
Inspired O_2	blue
Heart rate	green
Tidal volume	pink

Table 3. Answers on type of trend representation

trend presentation	# anesthetists	# anesthesia residents	# Nurse anesthetists	# Total
Number	1	0	1	**2**
Length	0	1	0	**1**
Thickness	2	4	4	**10**
none	2	0	0	**2**

Chapter 6. Design of monitor types

We decided to build our metaphorical anesthesia monitor in Java J2SE 5. Java is a cross-platform language that includes multiple libraries suitable for designing anesthesia monitors.

6.1. Classic monitor

The presented classic monitor (Fig. 14) in the experiment is based on the monitors in the operation room. All variables that were discussed in chapter 2 are represented in the monitor.

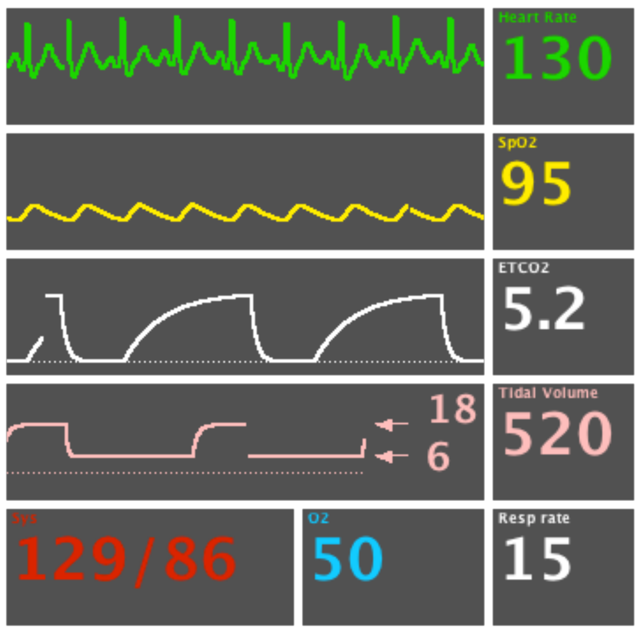

Figure 14. Classic anesthesia monitor

6.2. Metaphorical monitors

6.2.1. Metaphorical Anesthesia Interface (MAI)

The pilot results provided design considerations for the new metaphorical anesthesia monitor based on the requirements for anesthetists/anesthesia residents/nurse anesthetists. Our design goal was to implement these design considerations into the new metaphorical monitor to maximize user satisfaction and increase recognition speed for complications in an anesthesia monitoring task.

In the new monitor we chose to present the 9 variables that anesthetists, anesthesia residents and nurse anesthetists indicated as most important. Temperature was not included in the interface, because in most anesthesia monitors temperature is not presented. Instead, respiratory rate was added to the new interface, because this variable is currently presented in most anesthesia monitors.

We chose to divide the monitor in two systems: the vascular and respiratory system. All vital variables, presented in the new monitor (Fig. 15), are part of either the vascular or respiratory system. At the top of the screen two icons are presented, representing the respiratory system (left) and vascular system (right). Variables in the respiratory system are inspiratory O_2, expiratory CO_2, respiratory rate, tidal volume, PEEP and PAW pressures. The vascular system consists of the variables SPO_2, heart rate and blood pressure. Each variable is presented as a colored rectangle. The colors of all variables are based on the anesthetist preferences in the pilot research. Anesthetists red-green color-blindness can also distinguish these colors (Fig. 16). 6-9 percent of Caucasian males suffer from this type of color-blindness (Ganley & Lian, 1997). The colored rectangles are situated in a black frame that represents the steady-state value for this particular patient.

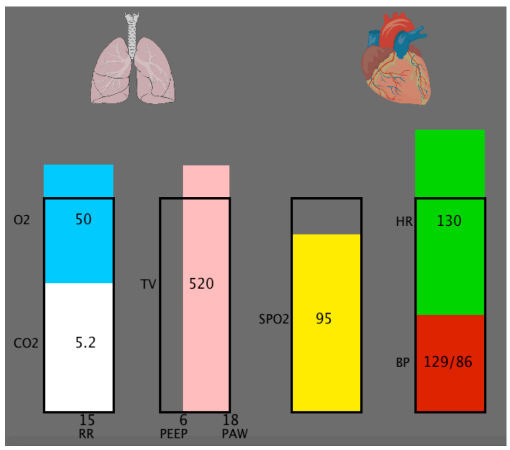

Figure 15. Metaphorical Anesthetist Interface

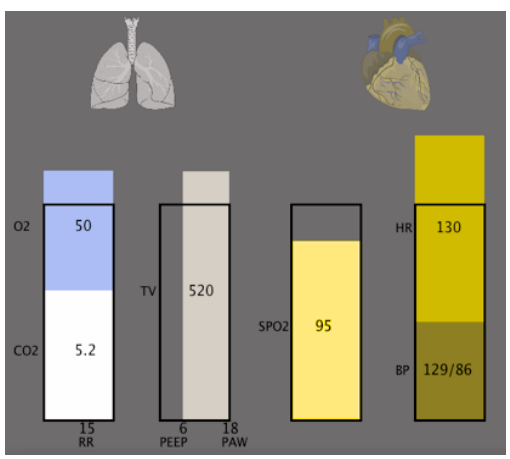

Figure 16. Metaphorical Anesthetist Interface (red-green color blindness)

Table 4. Steady-state values for the variables on the metaphorical monitor

Variable	Value
End tidal CO_2	4.3 kPa
Fraction of inspired O_2	45%
Respiratory rate	15 resp./min
Tidal volume	450 mmHg
PEEP	2 cmH_2O
PAW	18 cmH_2O
Saturation SPO_2	100%
Blood pressure	125/83 mmHg
Heart rate	75 bpm

The steady-state values for the variables in the metaphorical monitor were based on a male patient in rest with weight of 70 kilos and height of 1.78 meter, see table 4 for these values. The height of each rectangle represents the value of the corresponding variable. Rectangular heights change proportionally with the value of each particular patient variable. Other than the vertically presented variables, PEEP, PAW and respiratory rate are presented in a horizontal way: The width of the rectangles that represent these variables, changes proportionally with the value of each variable. Respiratory rate can only change in one direction (right) and PEEP/PAW in two directions (i.e. PEEP changes the left margin and PAW changes the right margin). Respiratory rate and PEEP/PAW are presented horizontally because these variables are parameter settings on the ventilator machine. The amount of inspiratory O_2 is also a parameter from the ventilator machine, but we chose to present inspiratory O_2 stacked with expiratory CO_2 because 8 of 15 subjects (53.3%) in the pilot preferred the presentation of both gases in one frame. Heart rate and blood pressure were also stacked in this manner, because 10 of 15 subjects (66.7%) preferred this presentation. In the frames with stacked rectangles, the combined steady-state value is reached when both values of the variables are normal. For example, when CO_2 is higher than the steady-state value and O_2 equals its steady state value, the rectangle for CO_2 partly pushes the O_2 rectangle out of the frame.

The first respiratory block contains the fraction of inspired O_2, end tidal CO_2 and respiratory rate. O_2 and CO_2 are stacked vertically, as a function of respiratory rate. This stack was chosen because errors in the ventilator machine could affect all three variable values directly: O_2 is driven into the lungs and CO_2 is extracted from the lungs at a certain respiratory rate. A decline in respiratory rate has a direct effect on the applied O_2 and produced CO_2, thus one frame provides an overview over the status of the ventilator machine.

The second block shows the patient's tidal volume vertically as a function of PEEP and PAW pressures. The chosen procedure of ventilation is pressure controlled, and the shape of this block is a presentation of lung compliance. Lung compliance is the amount of ductibility as a function of the applied pressure. A flat and wider block (i.e. low tidal volume, higher PAW) could indicate that the lungs have a lower compliance than expected in normal lungs.

The third block represents Oxygen saturation in the blood (SPO_2). Pilot results show that subjects did not agree upon which system SPO_2 belonged to. Thus, the representation of SPO_2 is situated somewhat between the cardiovascular system and respiratory system.

The fourth block in the interface consists of the values for heart rate and blood pressure. These variables are stacked in the monitor because a physiological relation is suggested between these properties. A patient might not be anesthetized enough and experiencing pain during surgery, which cause stress in the patient. In a stressed patient, blood pressure and heart rate will increase. In the metaphorical interface this is presented by a visual accumulation of both boxes. The opposite occurs when the anesthesia for a patient is too deep, which is also not desirable. Another argument to stack heart rate and blood pressure is the reflexive response from the body when one of both variables changes. For example, the heart rate will increase when the blood pressure decreases. This is not necessarily an acute complication. In the metaphorical interface, this situation is presented by a decreased rectangular height for blood pressure and increased rectangular height for heart rate. In this situation, the total steady-state value is not necessarily exceeded.

6.2.2. Metaphorical Anesthesia Interface with trends (tMAI)

tMAI (Fig. 17) is the metaphorical anesthetist interface (MAI) presented in chapter 6.2.1. with added trend information in the cardio-vascular system. We chose not to present trend information in the respiratory system, because an arrow represents the trend of each variable. The trend arrow provides the anesthetist with information about the direction of the change; the variable's value increases (arrow up) or decreases (arrow down). The arrow also represents the speed of the trend (i.e. how fast is the change of the variable's value). Trend speed is divided in three classes: low, medium and high (Fig. 18).

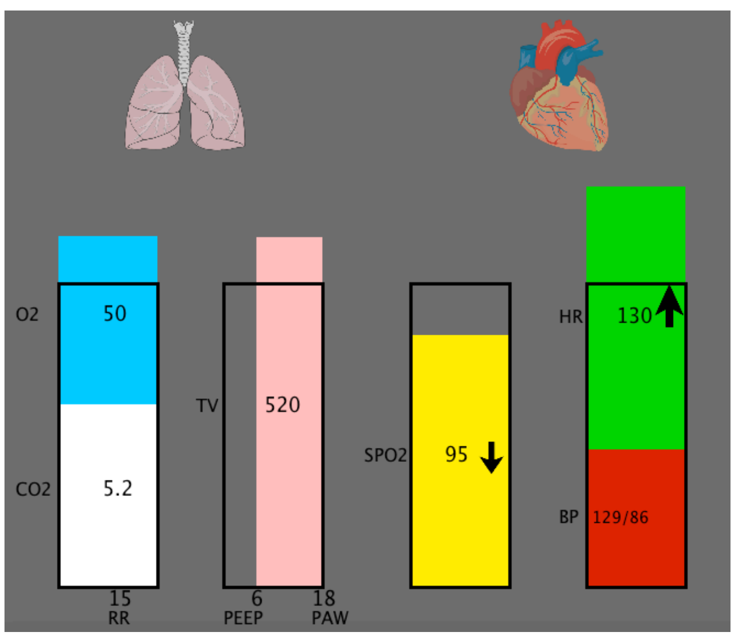

Figure 17. Metaphorical Anesthetist Interface with trend information

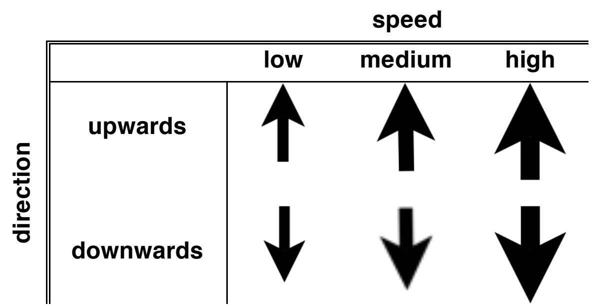

Figure 18. speed representation for trend arrows

6.3. Redundant monitors

We designed 2 redundant monitor types for the experiment. These monitors consist of both Metaphorical and Classic monitor combined and display exactly the same patient information.

6.3.1. Classic Monitor + Metaphorical Anesthesia Interface (MAI)

The first redundant monitor is a combination of the classic interface and the metaphorical anesthesia interface (Fig. 19).

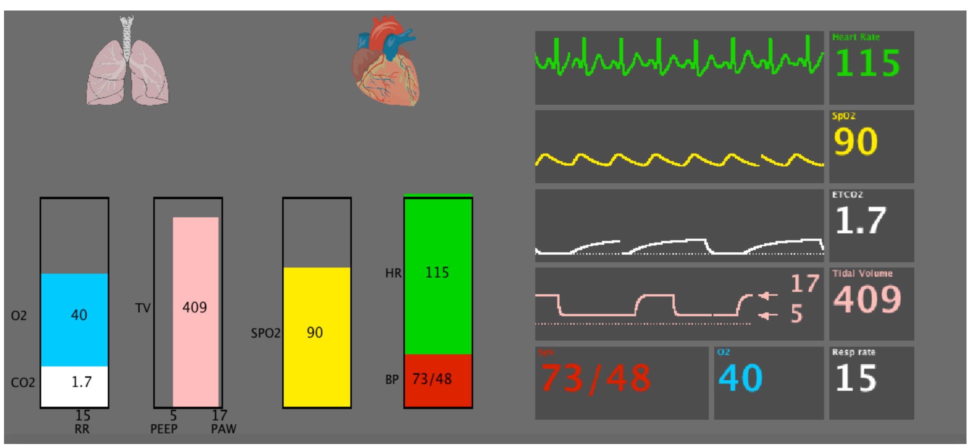

Figure 19. Metaphorical Anesthesia interface combined with classic monitor

6.3.2. Classic Monitor + Metaphorical Anesthesia Interface with trends (tMAI)

The second redundant monitor is a combination of the classic interface and the metaphorical anesthesia interface with trend information (Fig. 20).

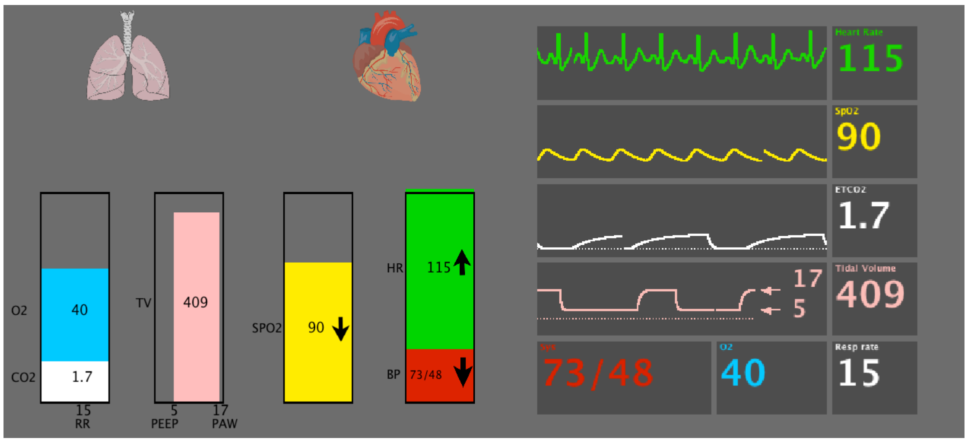

Figure 20. Metaphorical Anesthesia interface with trend information combined with classic monitor

Chapter 7. Experiment

7.1. Introduction

In our experiment we tried to answer the following question: does a metaphorical visualization of patient variables have a more positive effect on anesthetist recognition time of complications compared to a traditional monitoring display? To answer this question we provided anesthetists and anesthesia residents with a monitoring task. We hypothesize that:

1. anesthetists and anesthesia residents will recognize complications faster with the new metaphorical monitor compared to the classic monitor.

The new metaphorical monitors as described in chapter 6 were compared to the classic anesthesia monitor by providing subjects with static monitor screenshots of anesthesia-related complications. Response times were measured for the time it took to recognize the complication and deciding which action to perform. Our experimental setting differs from the setting of Michels et al. (1997). Whereas Michels et al. (1997) tested anesthetists' monitoring behavior in a dynamic simulator, we provide subjects with only a static monitor image. This allows us to focus mainly on subjects' behavior in viewing the patient monitor. Another difference with the study of Michels et al. (1997) is that we present subjects with ten different complications, instead of four different complications. This larger set of complications was chosen to provide subjects with a more complex task that approaches a real-life situation more realistically. In the experiment we also tested two additional hypotheses:

2. anesthetists and anesthesia residents will recognize the complications faster in monitors with trend information compared to the monitors without trend information.
3. anesthetists and anesthesia residents will recognize the complications faster in monitors with redundant information compared to the monitors without redundant information.

7.2. Method

7.2.1. Subjects

20 clinicians of the department of anesthesiology at the University Medical Center Groningen (UMCG) participated in the experiment; 10 Anesthesiologists (mean age = 44.6 yr; sd = 10.65 yr; mean experience: 15.6 yr; sd = 9.62 yr) and 10 Anesthesia residents (mean age = 32.4 yr; sd = 1.90 yr; mean experience = 3.6 yr; sd = 2.72 yr). Subjects were recruited on relatively "silent" moments in their daily work routine. Anesthetists and anesthesia residents could be called back to their current Operation Room during the experiment; six subjects had to quit early and finish the experiment at a later time.

7.2.2. Stimuli and apparatus

In the experiment, screenshots of the monitors were presented to the subjects. Each screenshot consisted values of “measured” patient variables displayed on one of five monitor types. A screenshot represented the occurrence of a specific anesthesia-related complication. 11 different patient situations (10 complications and 1 distractor) were presented in each experimental block (i.e. presentation of a specific monitor type).

The complications that were used in the experiment (see table 5) were chosen in dialogue with an experienced anesthesiologist. From a preliminary set of 13 complications, ten complications were selected. Three complications were not used in the experiment, because these were too similar to at least one other complication. The following complications were used in the experiment:

Air embolism: Bubble(s) of air have entered the vein(s). When this air becomes lodged in the pulmonary vessels and is prevented from flowing from the right ventricle to the lungs this can lead to death. Patient variables that deviates from normal indicating air embolism in the experiment are high heart rate (110-130 bpm), low blood pressure (Systolic 70-90 mmHg), low saturation (85-90%) and low expirational CO_2 (1.6-3.3 kPa). See Fig. 21.

Anaphylaxia: Allergic reaction that triggers a shock reaction in the body. Patients can be allergic to anesthetics or other substances that they are given during surgery. Patient variables that deviate from normal indicating anaphylaxia in the experiment are high heart rate (110-130 bpm), low blood pressure (70-90 mmHg) and low tidal volume (150-250 ml). see Fig. 22.

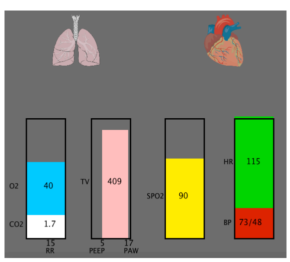

Figure 21. Representation of Air embolism

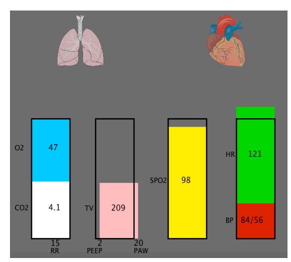

Figure 22. Representation of Anaphylaxia

Anesthesia depth insufficient: the patient is not sedated properly. He/she experiences pain, is able to move or is not unconscious. In the experiment, the patient variables that deviate from normal indicating insufficient depth of anesthesia are high heart rate (110-130 bpm), high blood pressure (Systolic 160-180 mmHg). See Fig. 23.

Bradycardia: the patient has a resting heart rate of below 60 beats per minute. A heart rate that is too low can lead to cardiac arrest. In the experiment, the patient variables that deviate from normal indicating bradycardia are low heart rate (30-45 bpm), low blood pressure (Systolic 80-100 mmHg). See Fig. 24.

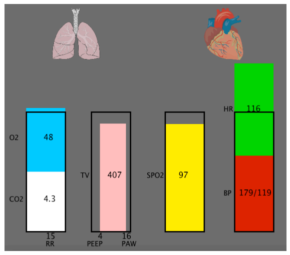

Figure 23. Representation of Anesthesia depth insufficient

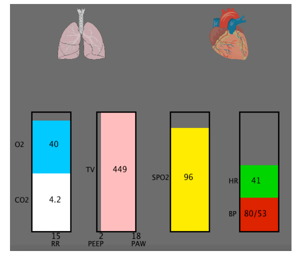

Figure 24. Representation of Bradycardia

Diffusion error: In the experiment, the patient variables that deviate from normal indicating diffusion error are low saturation (70-90%), high CO_2 (5.0-6.0 kPa) and low tidal volume (250-350 ml). See Fig. 25.

Faulty Oxygen supply: the patient is not provided with enough oxygen from the ventilator machine. In the experiment, the patient variables that deviate from normal indicating faulty Oxygen supply are low saturation (70-80%), low expirated CO_2 (3.3-4.0 kPa) and low inspired O_2 (5-15%). See Fig. 26.

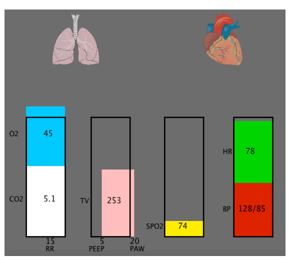

Figure 25. Representation of Diffusion error

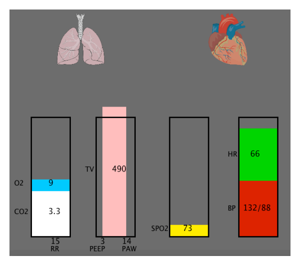

Figure 26. Representation of Faulty Oxygen supply

Hypoventilation: the concentration of CO_2 in the patient is too high. In the experiment, the patient variables that deviate from normal indicating hypoventilation are low saturation (92-95%), high CO_2 (5.0-6.0 kPa), low tidal volume (150-250 ml). See Fig. 27.

Tachycardia with sepsis: the patient shows an increase in heart rate as well as an increase in metabolic rate. In the experiment, the patient variables that deviate from normal indicating tachycardia with sepsis are high heart rate (110-130 bpm), low blood pressure (Systolic 70-90 mmHg), low saturation (94-99%) and high CO_2 (5.0-6.0 kPa). See Fig. 28.

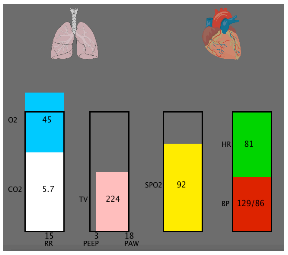

Figure 27. Representation of Hypoventilation

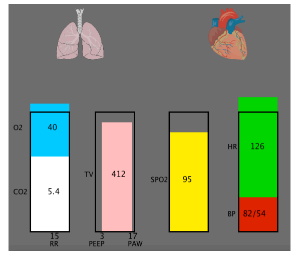

Figure 28. Representation of Tachycardia with sepsis

Tension pneumothorax: occurs when the patient's lung is punctured and air is driven mechanically into the pleural space. This increases tension on the lungs, which decreases the amount of air that can be inhaled. In the experiment, the patient variables that deviate from normal indicating tension pneumothorax are high heart rate (130-150 bpm), low blood pressure (Systolic 70-90 mmHg), low saturation (70-90%), low CO_2 (1.6-3.3 kPa) and low tidal volume (250-350 ml). See Fig. 29.

Ventilation stop: the patient is not mechanically ventilated anymore due to an error in the machine or loose hose. In the experiment, the patient variables that deviate from normal indicating ventilation stop are low saturation (70-90%), low expirated CO_2 (0-0.4 kPa), low PEEP (0-2 cmH_2O), low PAW (0-5 cmH_2O) and low tidal volume (0-100 ml). See Fig. 30.

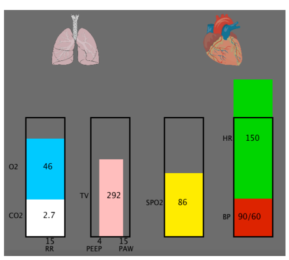

Figure 29. Representation of Tension pneumothorax

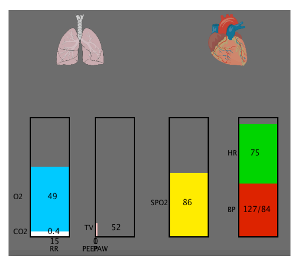

Figure 30. Representation of Ventilation stop

Distractor (Pulmonary secretions): In the experiment, the patient variables that deviated from normal indicating the distractor complication pulmonary secretions are low saturation (90-93%) and low tidal volume (250-350 ml). See Fig. 31.

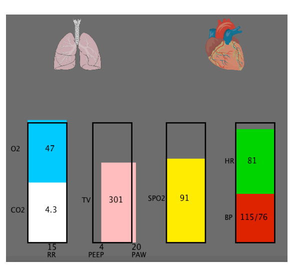

Figure 31. Representation of Pulmonary secretions (distractor complication)

For the experiment, 13 different actions were selected in dialogue with an experienced anesthesiologist. In each trial, subjects were asked to choose an action to treat the presented complication (table 6).

Table 5. The complications presented in the experiment, with their associated appropriate actions.

Complication	Appropriate action
1. Air embolism	100% Oxygen or Vasopressors / Cardiotonica
2. Anaphylaxia	Vasopressors / Cardiotonica
3. Anesthesia depth insufficient	Deepen anesthesia
4. Bradycardia	Atropine
5. Diffusion error	increase FiO_2 or increase PEEP or Furosemide
6. Faulty Oxygen supply	Check/correct Oxygen supply
7. Hypoventilation	Increase respiratory minute volume, Increase inspiration pressure
8. Tachycardia with sepsis	Vasopressors / Cardiotonica or Refill blood
9. Tension pneumothorax	Apply thorax drain
10. Ventilation stop	Manual respiration or Increase respiratory minute volume or Increase inspiration pressure
11. Pulmonary secretions (distractor)	

In each trial (see Appendix D for visualization of trials), subjects were presented with questions about the displayed complication. Three questions were asked in each trial and subjects answered those questions by clicking a button.

1. A monitor shows patient variables together with a button containing the text “I know it!”. Subjects clicked this button whenever they thought to have gained enough information from the monitor to choose an appropriate action and diagnosis for the presented situation.
2. The monitor disappeared and the action question (What is your first action in this situation?) appeared together with the possible actions (See table 6).
3. The diagnosis question (What will be your diagnose with this complication?) appeared together with the possible diagnoses (See table 5).
4. An empty screen appeared with a button containing the text: “I am ready for the next complication”.

Table 6. Possible answers for initial actions in experiment

Action
1. 100% Oxygen
2. Apply thorax drain
3. Atropine
4. Check/correct Oxygen supply
5. Deepen anesthesia
6. Furosemide
7. Increase FiO_2
8. Increase inspiration pressure
9. Increase PEEP
10. Increase respiratory minute volume
11. Manual respiration
12. Refill blood
13. Vasopressors / Cardiotonica

The experiment was run on an Apple MacBook Pro, Intel Core 2 Duo 2.26 GHz, 2 GB DDR3 SDRAM. The computer was equipped with 13.3-inch glossy TFT LED backlit display (1280 x 800 pixels) at 80% brightness. The input device for the experiment was an external 2-button mouse. The experimental setting was created in Java J2SE 5.

7.2.3. Experimental design

At the beginning of the experiment, subjects were informed about the available choices in complications and actions. It was emphasized that their response times were measured. They were told that during the whole experiment, the patient remained the same: a man in rest weighing 70 kilos and with a height of 1.78 meter. The experiment's duration was approximately 45-60 minutes.

55 experimental trials (5 blocks x 11 trials) and 25 practice trials (5 blocks x 5 practice trials) were presented to each subject. The order of the blocks was determined using a Latin-Square design to control for a possible learning effect during the experiment (See Appendix C).

Subjects were presented with 5 blocks, whereas in each block another monitor type was presented (classic, metaphorical, metaphorical + classic, metaphorical with trends, metaphorical with trends + classic). The set of trials in each block started with 5 practice trials, followed by 11 experimental trials: 10 complications and 1 distractor. The distractor trial was added to avoid that subjects could predict which complication would be presented in the last trial. There were 5 sets containing randomly assigned orders of complications. The sets with complications were presented to all subjects in the same order.

The practice trials were intended for subjects to get acquainted with the presentation of information in each monitor. In the practice trials, the monitors presented patient variables with randomly assigned variable values. Subjects were told that there were no right or wrong answers in the practice trials, because these presentations did not represent real complications. Subjects were also told to answer the practice trials randomly. After the practice trials, subjects started the experiment by clicking the button "Start real experiment" and they were told that the following trials represented real complications. During the experiment, response times between presentation of the monitor and mouse click, on the "I know it!!" button, were recorded.

7.2.4. Measures

During the experiment, response times were measured and answers on diagnosis questions and action questions were logged. Response times were an assumed measure for recognition performance for complications and in our analysis we compared response times for the different monitors. All monitor types were presented to each subject. This repeated-measures design controls for inter-subject variability of response times. The number of correct identifications of the complication and appropriate action are an assumed measure for diagnosing a complication and choosing an appropriate action in a real-life situation.

Chapter 8. Results

In the experiment, we tested whether the display with metaphorical visualizations of patient variables led to a decrease in recognition time of complications in anesthetists and anesthesia residents. We compared response times for metaphorical and classic interface to show the influence of a metaphorical interface on the recognition speed of complications. Furthermore, we were interested in the influence of trend information on the recognition speed. This was tested by comparing trend monitors with non-trend monitors. We analyzed the effects of redundancy (metaphorical with and without trend information as an addition to the classic monitor) on the recognition speed of complications compared to a single monitor. In chapter 8.1. we present the results for the effect of the metaphors, trend information and redundancy on response times for the recognition of complications. In chapter 8.2. we show the performance of anesthetists/anesthesia residents in correctly diagnosing the complications and selecting the correct treatment. In chapter 8.3. we show the results for differences in response times between anesthetists and anesthesia residents. In chapter 8.4. the results for a possible learning effect are presented.

8.1. Effects for monitor type

8.1.1. Effect of metaphors

Our main analysis focuses on the effect of monitor type on the response times in recognition of complications. In this analysis, only trials with correctly identified complications were utilized, because only properly identified complications are indicative for anesthetist's performance on recognition. A one-way repeated-measures ANOVA (Huyn Feldt corrections) shows no main effect of monitor type on response times in the experiment, $F(4,76) = 0.81$, $p = 0.52$ (see Fig. 32). To focus on the effects of metaphors on response times, we further analyzed the contrast between Classic and Metaphorical Anesthetist Interface (MAI). Contrasts reveal no significant difference in response times for the classic monitor (mean = 9.87 s, sd = 2.01 s) compared to response times for the MAI monitor (mean = 9.51 s, sd = 2.40 s), $F(4, 76) = 0.22$, $p = 0.64$. Thus, we conclude that the metaphors are not responsible for a faster recognition of complications in the experiment. We present all contrast between the different monitor types in table 7. In addition, we also analyzed the main effect of monitor type on response times for all trials (i.e. with either correct and incorrect identifications of complications). There was no significant main effect found, $F(4; 76) = 0.70$, $p = 0.57$.

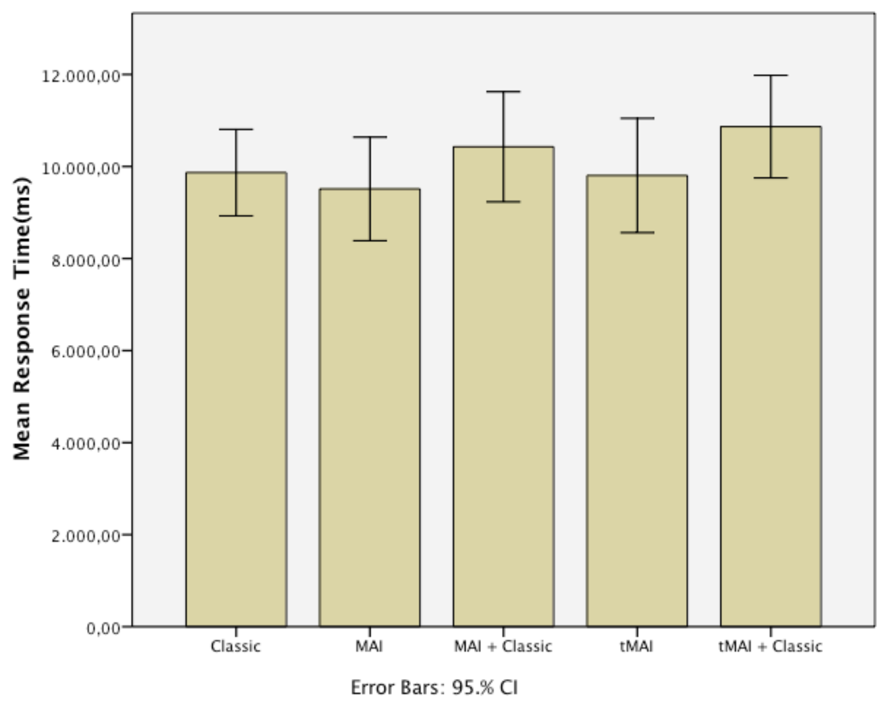

Figure 32. Response times between monitor types

Table 7. Contrasts for response times between different monitor types

Contrast	F(4,76) value	P value
Classic vs. MAI	0.22	0.64
Classic vs. MAI + Classic	0.56	0.46
Classic vs. tMAI	0.01	0.94
Classic vs. tMAI + Classic	1.70	0.21
MAI vs. MAI + Classic	0.88	0.36
MAI vs. tMAI	0.10	0.75
MAI vs. tMAI + Classic	3.33	0.08
MAI + Classic vs. tMAI	0.52	0.48
MAI + Classic vs. tMAI + Classic	0.23	0.64
tMAI vs. tMAI + Classic	1.26	0.28

8.1.2. Effect of trends

In the experiment we also tested whether trend information in a monitor led to faster recognition of complications. In the analysis, we compared response times for the metaphorical trend monitors (i.e. tMAI and tMAI + classic) with the metaphorical non-trend monitors (MAI and MAI + classic). The classic monitor was not categorized as non-trend monitor, because of the lack of metaphors in this monitor. The results for the metaphorical trend monitors show no main effect for trend on response times. Metaphorical trend monitors tMAI and tMAI + classic (mean = 10,335 ms , sd = 1,369 ms) do not differ in response time compared to the metaphorical non-trend monitors (MAI and MAI + classic), (mean = 9,970 ms, sd = 1,179 ms), $F(1,19) = 0.48$, $p = 0.50$, (Fig. 33).

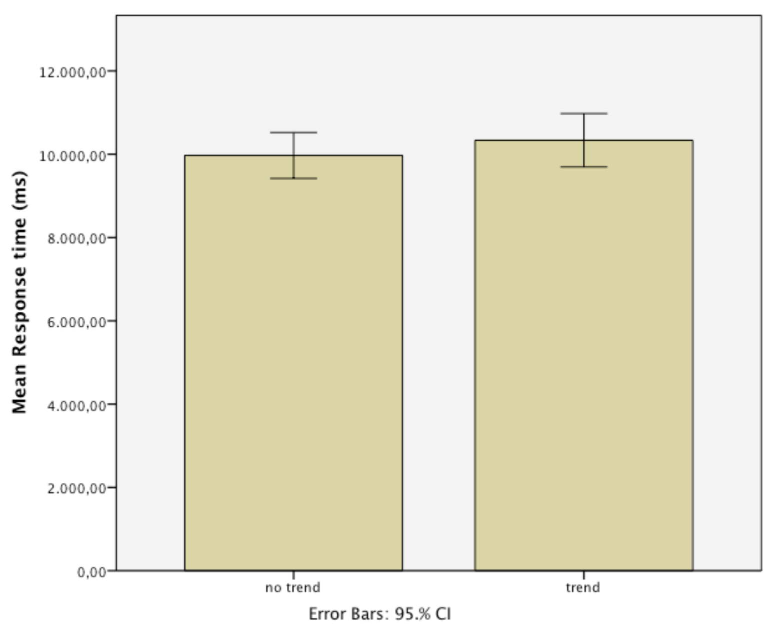

Figure 33. Response times trend vs. no-trend.
Trend monitors: tMAI and tMAI + Classic.
No-trend monitors: MAI and MAI + Classic

8.1.3. Effect of redundancy

We evaluated whether redundant monitors showed a positive effect on recognition speed. Classic, MAI and tMAI are single monitors, whereas MAI + classic and tMAI + classic present redundant patient information. A one-way repeated-measures (Huyn Feldt corrections) analysis showed no significant difference in response times between the single (mean = 9,728 ms, sd = 924 ms) and redundant monitors (mean = 10,647 ms, sd = 1,386 ms), $F(1,19) = 3,17$, $p = 0.09$: the addition of metaphorical information to a classic monitor setup does not help the anesthetist in faster recognition of complications in the experiment (Fig. 34).

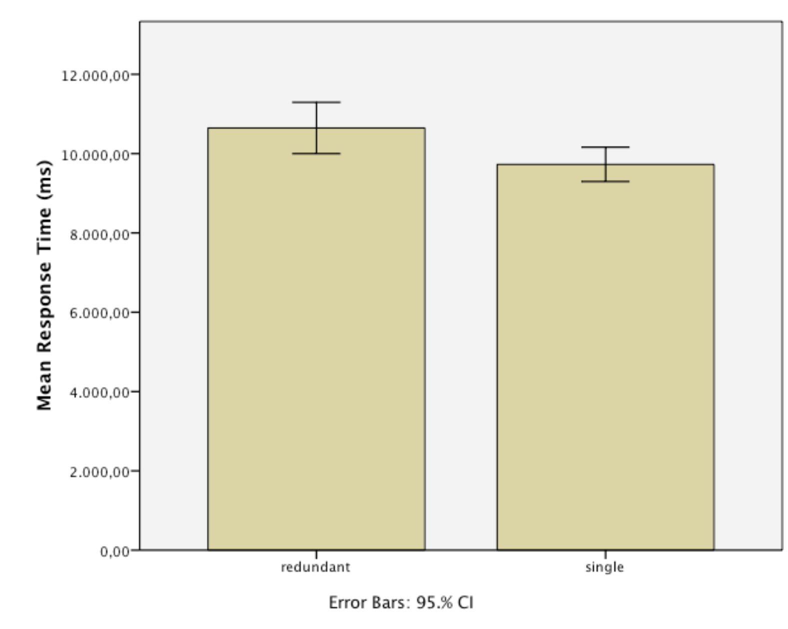

Figure 34. Response times for redundant vs. single monitors
Redundant monitors: MAI + Classic and tMAI + Classic
Single monitors: Classic, MAI and tMAI

8.2. Effects for groups

8.2.1. Within metaphorical monitor

We analyzed the presence of significant differences in response time between anesthetists and anesthesia residents with respect to the variate *monitor type*. The effect of groups (i.e. anesthetists and anesthesia residents) was analyzed with a one-way repeated-measure ANOVA (Huyn Feldt corrections).

No significant main effect of group was found between groups (see Fig. 35), $F(1,18) = 0.87$, $p = 0.36$. See table 8 for contrasts between groups. Within the group of anesthesia residents no significant main effect in response time between the monitors was present, $F(4,36) = 0.40$, $p = 0.81$. Within the group of anesthetists, results show also no significant main effect in response time between the monitors, $F(4,36) = 1.64$, $p = 0,19$.

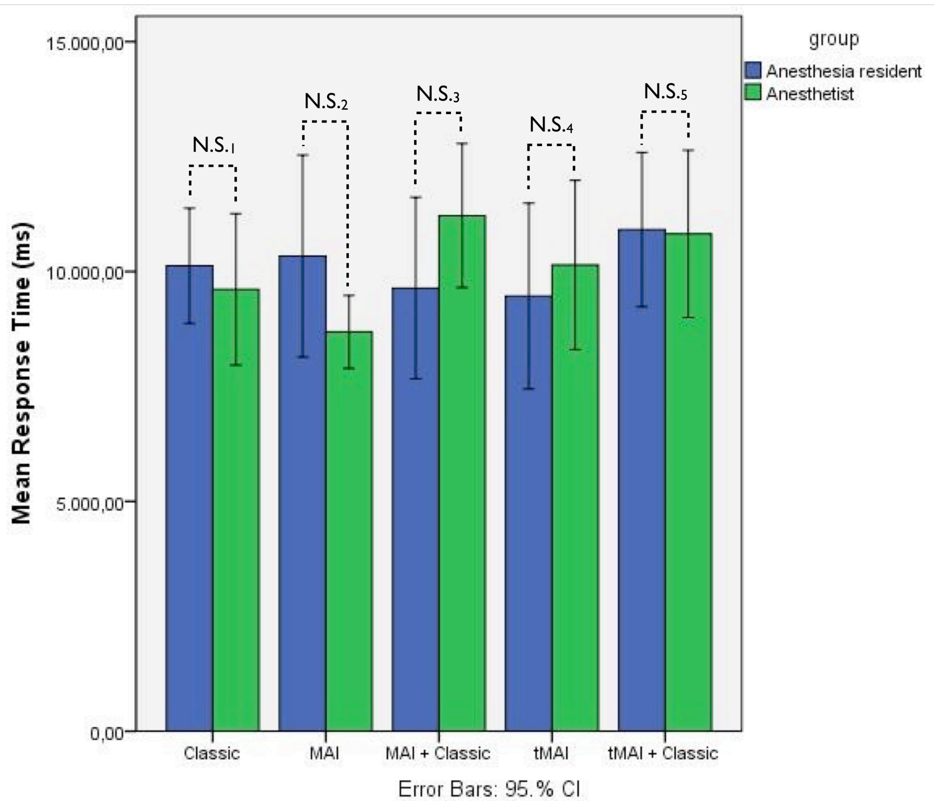

Figure 35. Response times between groups

Table 8. Statistics for monitor types

Monitor type	t-value, n=20	P value
Classic	0.56	0.58, N.S.$_1$
MAI	1.60	0.13, N.S.$_2$
MAI + Classic	-1.42	0.17, N.S.$_3$
tMAI	-0.56	0.58, N.S.$_4$
tMAI + Classic	0.09	0.93, N.S.$_5$

8.2.2. Within trend monitors

In the results for trend (tMAI, tMAI + Classic) vs. non-trend monitors (MAI, MAI + Classic), no significant main effect between groups was found, $F(1,18) = 0.31$, $p = 0.58$. See table 9 for contrasts between groups. Within the group of anesthetists no significant difference in response times between trend and no-trend monitors was found, $F(1,9) = 0.50$, $p = 0.50$. Within the group of anesthesia residents there was also no significant difference in response times between trend and no-trend monitors, $F(1,9) = 0.07$, $p = 0.80$ (see Fig. 36).

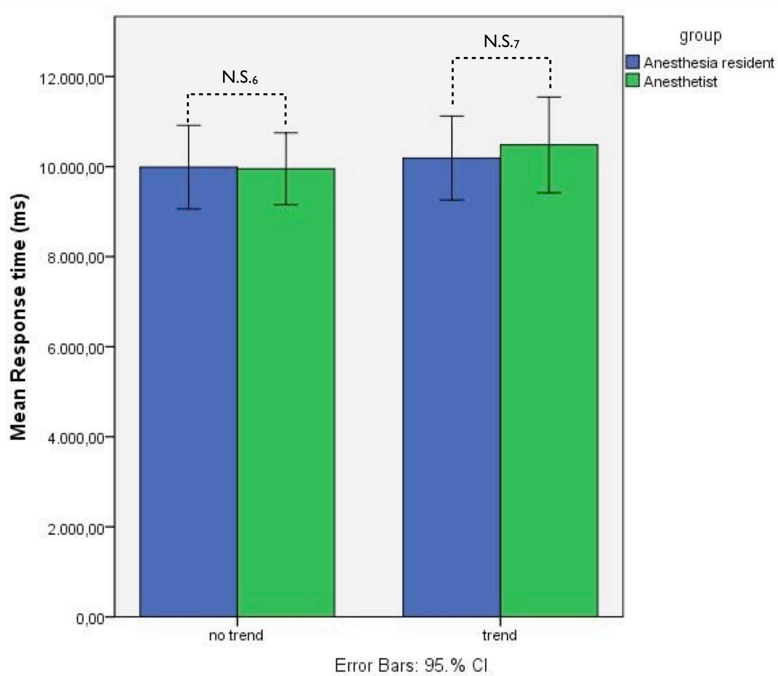

Figure 36. Response times for trend information

Table 9. Statistics for combined monitor types

Monitor type	t-value, n=20	P value
no trend	0.07	0.20, N.S.$_6$
trend	-0.47	0.65, N.S.$_7$
redundant	-1.21	0.24, N.S.$_8$
single	1.21	0.24, N.S.$_9$

8.2.3. Within redundant monitors

Overall results for redundant (MAI + Classic, tMAI + Classic) vs. single (Classic, MAI and tMAI) monitors show no main effect for groups, $F(1,18) = 1.47$, $p = 0.24$. See table 9 for contrasts between groups. Contrasts reveal a significant faster response within the group of anesthetists on the single monitors (mean = 9480.75, sd = 706.46) compared to response times of the redundant monitors (mean = 11018.16, sd = 1059.69), $F(1,9) = 7.58$, $p < 0.05$. No significant difference was found in the response times within the group of anesthesia residents between redundant and single monitors, $F(1,9) = 0.12$, $p = 0.73$ (see Fig. 37).

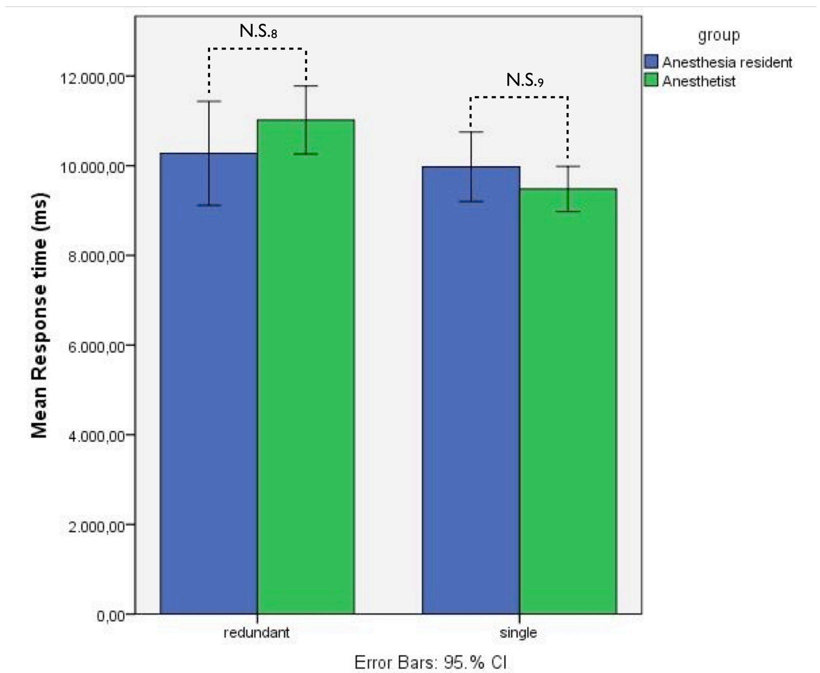

Figure 37. Response times for redundancy

8.3. Identification of diagnoses and actions

8.3.1. Diagnoses

In the experiment, subjects identified 42.4% of all complications incorrectly. Anaphylaxia, Diffusion, Air embolism and Tension pneumothorax all scored below a 50% correct identification (table 10). Identification scores for the complications varied highly; subjects identified *anaphylaxia* correctly, 10 percent of the time. In contrast, *anesthesia depth unsufficient* was identified correctly 100 percent of the time. This variability could indicate that the properties of some complications overlapped with properties of other complications. A *post-hoc* repeated-measures ANOVA showed no significant difference in identification scores between monitors, $F(4,36) = 1.335$, $p = 0.28$.

Frequency of incidence for the complications is shown in table 12. The afore-mentioned complications that were the least recognized have also the lowest occurrence in real life surgery.

Table 10. Number of trials with correct identification of the diagnosis for each monitor type.

	# trials					
Complication	**Classic**	**MAI**	**MAI + classic**	**tMAI**	**tMAI + classic**	**Total**
Anesthesia insufficient	20	20	20	20	20	**100**
Bradycardia	18	19	19	20	19	**95**
Failure in Oxygen supply	14	19	19	17	17	**86**
Hypoventilation	15	17	16	16	18	**82**
Tachycardia with sepsis	16	15	11	16	12	**70**
Ventilation stop	10	10	9	10	13	**52**
Tension pneumothorax	7	5	4	7	8	**31**
Air embolism	8	5	5	6	5	**29**
Diffusion error	4	3	4	5	5	**21**
Anaphylaxia	1	2	1	3	3	**10**
Total	**113**	**115**	**108**	**120**	**120**	**576**

Table 11. Number of incorrect diagnoses and actually selected diagnosis

# Correct diagnosis	# Selected diagnoses: Anaphylaxia	Diffussion error	Air embolism	Tension pneumothorax	Ventilation stop	Tachycardia with sepsis	Hypoventilation	Oxygen failure	Bradycardia	Anesthesia insufficient	**Total(%)**
Anaphylaxia	-	5	2	21	2	28	28	1	0	3	**90**
Diffussion error	0	-	2	2	3	2	67	5	0	0	**81**
Air embolism	13	9	-	18	0	24	7	0	0	0	**71**
Tension pneumothorax	10	3	20	-	0	23	12	1	0	0	**69**
Ventilation stop	0	1	7	5	-	0	18	18	0	0	**49**
Tachycardia with sepsis	17	4	0	0	2	-	5	0	0	2	**30**
Hypoventilation	1	9	0	0	5	0	-	0	0	0	**15**
Oxygen failure	0	5	2	1	1	0	3	-	0	0	**12**
Bradycardia	1	0	1	0	0	1	0	0	-	2	**5**
Anesthesia insufficient	0	0	0	0	0	0	0	0	0	-	**0**
Total (%)	**42**	**36**	**34**	**47**	**13**	**78**	**140**	**25**	**0**	**7**	**422**

Table 12. Incidence rate of complications of 1256 reported incidents (Webb et al. 1993)

Complication	**# incidents**
Anesthesia depth insufficient	No data
Ventilation stop	155
Oxygen failure	104
Bradycardia	68
Hypoventilation	47
Tachycardia	31
Air embolism	14
Diffusion error	13
Anaphylaxia	12
Tension pneumothorax	6

8.3.2. Actions

In each trial, subjects also chose which action they thought to be most appropriate for the presented complication. 52% of all actions were incorrectly chosen with the given complication. From these 463 incorrectly chosen actions, 130 times the action *100% Oxygen* was selected. Table 13. presents all actions that were incorrectly identified.

Table 13. Number of incorrect actions and actually selected action

Diagnosis	# Selected incorrect actions: 100% Oxygen	Apply thorax drain	Atropine	Check/correct Oxygen supply	Deepen anesthesia	Furosemide	Increase FiO2	Increase inspiration pressure	Increase PEEP	Increase respiratory minute volume	Manual respiration	Refill blood	Vasopressors / Cardiotonica	**Total incorrect**
Diffussion error	35							11		34	9			**89**
Anaphylaxia	5	17			2		3	5	2	22	6	26		**88**
Tension pneumothorax	33						7	2	1	6	6	13	13	**81**
Oxygen failure	43					1	11		2	1	9			**67**
Air embolism		13			1	2	4	1	2	1	2	15	14	**55**
Ventilation stop	9	6		16									2	**33**
Hypoventilation	3				1	2	3		8		9			**26**
Tachycardia	1				2	1	1	3	1	4				**13**
Bradycardia	1											2	8	**11**
Anesthesia insufficient														**0**
Total	**130**	**36**	**0**	**16**	**6**	**6**	**29**	**22**	**16**	**68**	**41**	**56**	**37**	**463**

8.4. Learning effect during experiment

8.4.1. Order of blocks

The analyses for the learning effect were performed on the whole dataset, regardless of the validity of the subjects' answer on the question.
A one-way repeated-measures ANOVA (Huyn Feldt corrections) showed a main effect for position of sets in the experiment, on mean response times, $F(1.8, 34.15) = 13.85$, $p < 0.001$ (Fig. 38). Contrasts reveal a significant increase in response times for the first set (mean = 17713.78 ms) compared to the second set (mean = 13301.05 ms), $F(1.8, 34.15) = 10.02$, $p < 0.01$. No significance is found between second and third set, $F(1.8, 34.15) = 0.11$, $p = 0.75$. Contrasts also revealed an increase in response times for the third set compared to the fourth set(mean = 11059.49 ms, $F(1.8, 34.15) = 17.73$, $p < 0.001$. No significance between fourth set and fifth set was found, $F(1.8, 34.15) = 2.67$, $p = 0.12$.

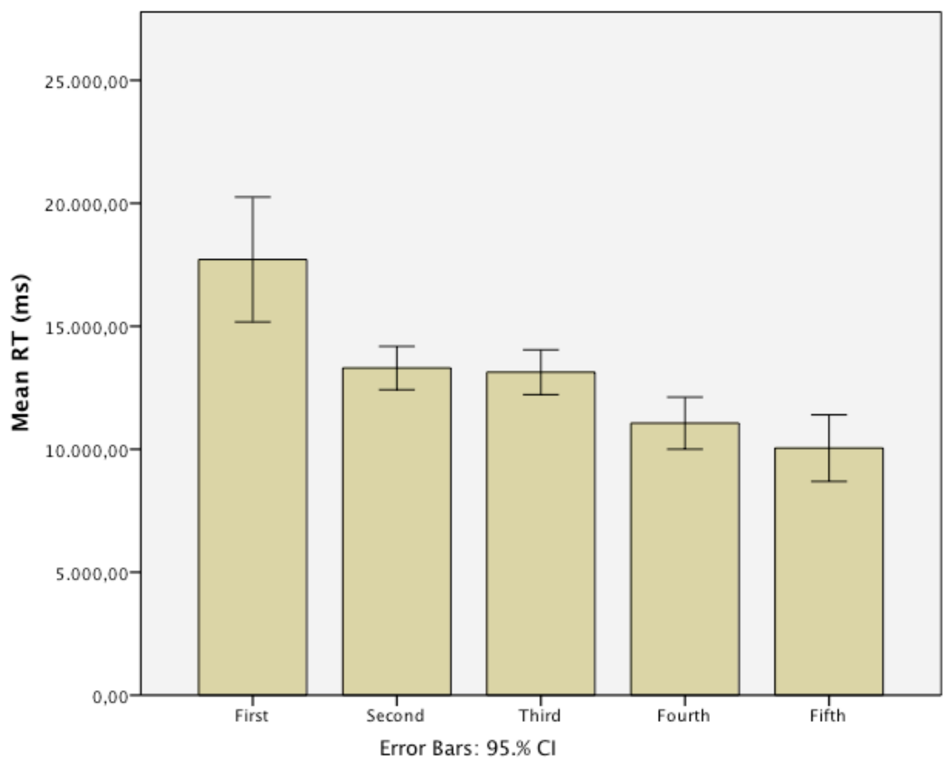

Figure 38. Mean response times for sets

8.4.2. Order of trials

We analyzed possible learning effects during the course of a block. A one-way repeated-measures ANOVA (Huyn Feldt corrections) showed a significant main effect for position of trials within an experimental block (Fig. 39), $F(9, 171) = 4.747$, $p < 0.05$.

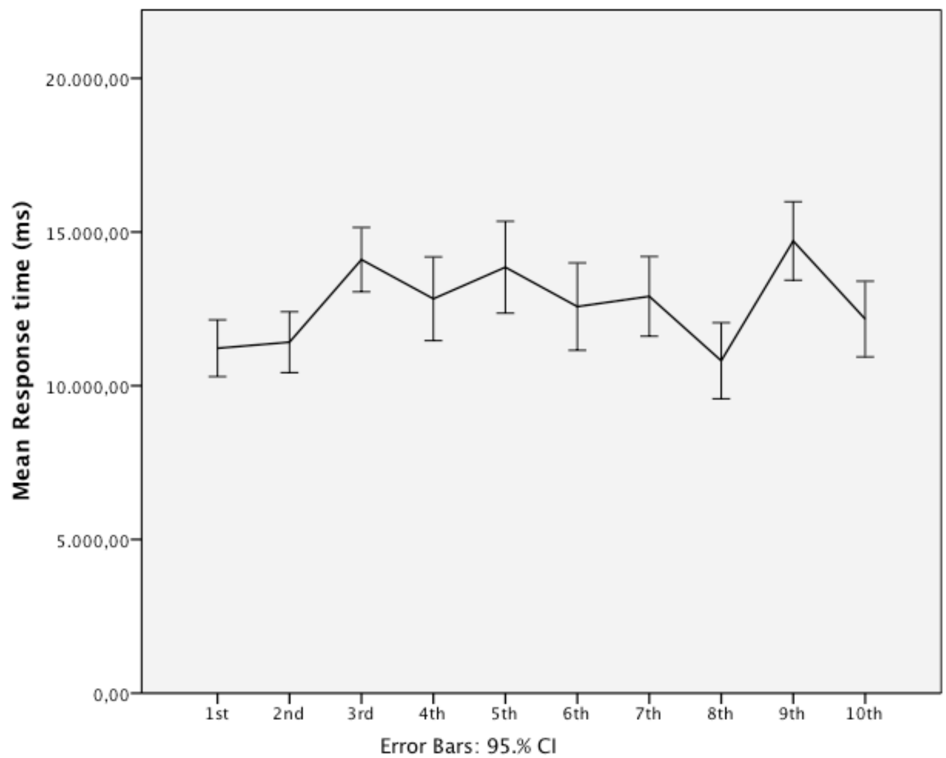

Figure 39. Response times on the trials in one block

Chapter 9. Discussion

In this study, we developed a new anesthesia monitor that displays metaphorical representations of patient variables. This monitor is based on the IGAD monitor (Michels et al. 1997) and the results from our pilot questionnaire. In the experiment we evaluated whether the metaphorical presentation of patient variables, in a static monitoring task, had a positive effect on anesthetists' recognition performance of complications compared to a traditional anesthesia monitoring display. Response times for processing visual monitoring information were assumed to measure the time it took for anesthetists/anesthesia residents to recognize complications. Scores for selecting the correct diagnoses were logged for each subject and these scores were assumed to measure the identification of complications.

This chapter presents the discussion of the experimental results. In paragraph 9.1, we discuss the effects on recognition time of complications for the different monitors (i.e. metaphorical, redundant and trend monitors) and paragraph 9.2 focuses on the differences in response times between anesthetists and anesthesia residents. The identification scores of diagnoses are discussed in paragraph 9.3. We propose ideas for further research in anesthesia monitors and decision support in paragraph 9.4.

9.1. Monitor effects

9.1.1. Effect of metaphors

We hypothesized that anesthetists and anesthesia residents would recognize the complications faster with the metaphorical monitor compared to the classic monitor. Michels et al. (1997) showed in an anesthesia simulation task that subjects recognized complications faster with the IGAD metaphorical monitor compared to a classic anesthesia monitor. In the results from our experiment, we found no difference in response times for the metaphorical monitor compared to classic monitor. Although we cannot conclude that metaphorical monitors help anesthetists and anesthesia residents in faster recognition, the response times of the metaphorical monitor were also not slower compared to the classic monitor. This result suggests that although our subjects had a mean experience of 3.6 years (sd = 2.72 years) in working with a classic anesthesia monitor, they did not recognize the complications faster with the familiar classic monitor compared to the unfamiliar metaphorical monitor. This could indicate that only a relative small period of practice time is needed for the metaphorical interface to obtain response times that are equally fast compared to the classic interface. An explanation for the lack of effect in response times between the new metaphorical and the classic monitor could be due to the small period of practice time on the new metaphorical monitor and familiarity with the classic monitor. The number of correctly identified complications did not differ significantly between metaphorical monitor and classic monitor. This result indicates that the accuracy of variable interpretation did not decrease in the metaphorical monitor compared to the classic monitor.

9.1.2. Effect of trends

Our second hypothesis was that anesthetists and anesthesia residents would recognize the complications faster in monitors with trend information compared to the monitors without trend information. We predicted that the presentation of trend information in a metaphorical monitor would increase saliency for the deviating variables and thereby driving anesthetists'/anesthesia residents' attention toward these variables. This prediction was based on considerations in studies on attention to visual cues (Tappan et al. 2009; Ballast, 1992).

The presentation of trend information in the metaphorical monitor did not result in faster response times compared to the monitors without trend information (metaphorical and classic). This result is interesting because most anesthetists in the pilot research expected that trend information would be a valuable addition to an anesthesia monitor. By presenting screenshots in the experiment we tried to simulate only a restricted part of the anesthetist's job: the experiment was purely a static monitoring task, whereas trend information shows the change of a variable in a period of time. We hypothesized that trend information would provide the anesthetists with more clues on to what variables needed to be attended. We think that the positive effect of the presentation of trend information in a static monitoring task on recognition performance was counterbalanced by another unexpected effect. The anesthetist might change from non-analytical to reflective reasoning when the presented with trend information on a monitor in a static task. Mamede et al. (2007) studied the change of non-analytical to analytical reasoning in clinicians. Whereas clinicians appear to reason non-analytical, (i.e. based on pattern-recognition of symptoms) in diagnosing straightforward cases, ambiguity in clinical cases can result in a shift towards analytical reasoning. Trend information in a static task can be considered an added ambiguous symptom of the presented case, since trends implicate that the presented static complication originated from a dynamical situation. The presentation of trend information in the experiment could make that anesthetists/anesthesia residents shift from non-analytical to analytical reasoning in reasoning about the presented symptoms. This shift could indicate why there appears to be no decrease in recognition time in the trend monitor for anesthetists/anesthesia residents.

9.1.3. Effect of redundancy

We hypothesized that subjects would show a faster response in recognizing complications when viewing the redundant (metaphorical + classic and metaphorical with trends + classic) monitors compared to the single (metaphorical, metaphorical with trends and classic) monitors. The visual representation of metaphors can be considered a pattern of patient information, whereas the classic monitor represents numerical values and curves. We expected that anesthetists/anesthesia residents would choose their preferred representation based on the current situation.

No difference was found in response times between the single and redundant monitors. The combination of both visualizations did not lead to a faster recognition of complications contrary to what was expected from the redundancy gain theory (Miller et al. 1982; Wickens et al. 2004). However, we also did not found a slower recognition of complications. This could indicate that the positive effect of a combined visualization is counteracted by another effect. We think that redundancy of information could also have distracted subjects in their scanning behavior, which could have led to slower recognition of the presented pattern.

9.2. Group effect

There was no main effect on response times between both groups (anesthetists and anesthesia residents). Thus, we can conclude that the level of experience has no influence on recognition speed of complications in our monitoring task.

9.3. Diagnosis performance

An interesting result from our experiment is the large amount of incorrect diagnoses. A number of explanations may account for this: first of all, subjects may not have been able to distinguish between different complications, perhaps because the combination of patient variables for each complication overlapped with other complications. To test this hypothesis we examined whether complications were mistaken for other complications. However, results show that the effect is uni-directional: Anaphylaxia is often mistaken for Hypoventilation but not vice versa. A more plausible explanation for the high number of incorrectly identified complications is the incidence of these complications in real life surgery. In clinical reasoning, it is a well-known phenomenon that high frequent occurring complications are better recognized than low frequent complications (Tversky & Kahneman, 1974). To test a possible relation between the frequency of complications in real-life and the scores on complications in our experiment we compared the complications from the experiment with results from the Australian Incidence monitoring study (Webb, 1993). In this study, 2000 anesthesia-related incidents were reported (table 9). We found a relation between the score on complications in our experiment and the real life frequency of incidence of these complications. It appears that complications with a low incidence in real-life are identified incorrectly more often in the experiment compared to complications that are more common in real incidents.

In the experiment we assumed that every complication was equally difficult to recognize for an anesthetist. However, our results suggest that complications differed in complexity based on the large variability of correct identifications between complications (table 14). We assumed that complications can be distinguished by intrinsic properties: the number of variables with values that deviate from steady-state, the amount of deviation from steady-state and the amount of variable overlap with other complications. For example, bradycardia appears to be a more recognizable complication compared to tension pneumothorax. In Bradycardia, only 2 variables deviate from normal (see table 14), while tension pneumothorax is defined by 5 deviating variables. The two target variables (Blood pressure and heart rate) in bradycardia are also both situated in the cardiovascular system, while the target variables (Blood pressure, heart rate, saturation, CO_2 and tidal volume) with tension pneumothorax are more scattered over both systems (see table 15).

We selected only complications with minimal overlap in variable values. Because the set of anesthesia-related complications is limited, it was impossible to choose a large variety of complications without overlap. An example of the influence of overlap is shown by the common confusion between Air embolism, Tachycardia and Anaphylaxia. All three complications show exactly the same deviation from steady-state for blood pressure and heart rate (table 15), but with the complication Air embolism, CO_2 value is very low. Complications Anaphylaxia and Tachycardia have respectively a normal CO_2 value and a CO_2 value that is too high. It appears that the confusion between these complications appears to be grounded on the overall real life frequency (i.e., Anaphylaxia,12; Air embolism, 14 and Tachycardia, 31) and the overlap of variables.

Table 14. features of complications

Complication	# deviating variables	Incidence rate (Webb, 1993)	Identification score
Anesthesia depth insufficient	2	No data	100
Bradycardia	2	68	95
Oxygen failure	3	104	86
Hypoventilation	3	47	82
Tachycardia with sepsis	3	31	70
Ventilation stop	4	155	52
Tension pneumothorax	5	6	31
Air embolism	4	14	29
Diffusion error	3	13	21
Anaphylaxia	3	12	10

Table 15. intrinsic features of complications. Deviations from steady-state value are presented on a scale from -3 (very low) to +3 (very high).

Complication	*HR*	*BP*	*SAT*	CO_2	*PAW*	*TV*	O_2
Anesthesia depth insufficient	+1	+1	0	0	0	0	0
Bradycardia	-1	-0.5	0	0	0	0	0
Oxygen failure	0	0	-2	-1	0	0	-1
Hypoventilation	0	0	-0.5	+3	0	-2	0
Tachycardia with sepsis	+1	-1	0	+3	0	0	0
Ventilation stop	0	0	-1.5	-3	-1	-3	0
Tension pneumothorax	+2	-1	-1.5	-2	0	-1	0
Air embolism	+1	-1	-1	-2	0	0	0
Diffusion error	0	0	-1.5	+3	0	-1	0
Anaphylaxia	+1	-1	0	0	0	-2	0

Finally, the high number of incorrectly identified complications can also be due to the static nature of the screenshots that were presented in the experiment. In real life, the occurrence of complications can be linked to knowledge about external factors. In certain cases, the anesthetist is able to predict that a complication will occur as a consequence of operative actions from the surgeon. For instance, an anesthetist can expect that blood pressure will decrease, when the patient is losing blood due to the wound that was created by the surgeon. These causally linked events were not present in the experiment. Anesthetists were deprived of important factors, such as time and context. This could have led to the low number of correctly identified diagnoses.

9.4. Further research

Further research of the anesthetists' scanning behavior is recommended. It should be interesting to study which information is exactly needed for an anesthetist to generate a correct diagnosis.
After each experiment, we asked the subject how they experienced the overall task. Almost all subjects declared to be frustrated about the static nature of the task. Another commonly heard complaint was the lack of patient information and external influences during the task.

We recommend focusing future experiments on the recognition of change in the patient variables. This can be obtained by presenting the anesthetist with a monitor in more dynamic environment. We think that with the increase of dynamism, a decrease in possible experimental complications is needed. The use human patient simulator can be used to create a setting that resembles a real operating theatre.

To support the anesthetist in complex tasks, there might be a role for a Decision Support System (DSS) in the operation room. In the interviews some anesthetists mentioned an interesting phenomenom; when a differential diagnosis is generated, it is very difficult to deviate from the chosen path. As some anesthetists declared, after a longer time period in surgery there is an increased risk for cognitive tunneling (Cook & McDonald, 1988, Kremer et al. 2002). Cognitive tunneling was also found by Schwid & O'Donnell (1992) in a study with the human patient simulator. During simulated complications, anesthetists with different grades of experience were asked to diagnose and treat each complication. Schwid & O'Donnell (1992) showed that 9 out of 30 anesthetists misdiagnosed or mistreated the patient due to cognitive tunneling at some point in the simulation. From our results we suggest further research to a DSS which main goal should be to help the anesthetist to remain objective in his/her diagnosis. The disability of the anesthetist to recognize complications merely by variable value configurations provides a possible role for a DSS.

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Appendix

A. Questionnaire pilot (dutch)

Vragenlijst Anesthesisten over vernieuwde interface voor patientmonitoring

Algemeen

1. Snapt u wat de verticale weergave van iedere variabele betekent? (Slide 1)

2. Snapt u wat de horizontale weergave van variabelen betekent?

Variabelen

1. Welke gegevens heeft u nodig om snel een solide diagnose te stellen? (Slide 1)

2. Ingeademde lucht vs. Uitgeademde lucht

3. PEEP vs. PAW (Slide 2)

4. Temperature vs. No Temperature

5. Sys/dia vs. Mean BP

6. Mist u verder nog gegevens?

Weergave van systemen

1. Snapt u de betekenis van de iconen?

2. Snapt u welke variabelen bij welke iconen horen?

3. Grote weergave achter blokken vs. Kleine weergave boven blokken

4. Vindt u de iconen handig?

Assen en waarden

1. Ziet u liever wel of geen assen? Waarom?

2. Is het voor u duidelijk welke waarden bij welke variabelen horen?

3. Vindt u dat de waarden voor variabelen op de goede plaats zijn weergegeven? Waarom?

4. Wat vindt u van de lettergrootte en lettertype?

Vorm

1. Welke weergave van sys/dia en heart rate prefereert u? Waarom?

2. Welke weergave voor informatie van ademhalingssysteem prefereert u? Waarom?

3. Ziet u de Loss en IV waarden liever geïntegreerd of als losse balken? Waarom?

4. Welke stapeling van HR en BP prefereert u? Waarom? (Slide 2 en 3)

5. Ziet u de waarden voor verdovende middelen liever geïntegreerd of als losse balken? Waarom? (Slide 3 en 4)

Kleuren

1. Heeft u associaties bij de verschillende kleuren? Welke?

2. Alle kleuren verschillend vs. Kleurbetekenissen (Slide 4 en 5)

3. Zijn er kleuren waarbij u moeite heeft om onderscheid te maken?

4. Prefereert u een wit of zwart kader? Waarom? (Slide 5 en 6)

5. Welke achtergrondkleur prefereert u? Wit of grijs? Waarom? (Slide 6 en 7)

Visuele trends

1. Snapt u de betekenis van de pijlen? (Slide 8)

2. Wat vindt u van de locatie van de pijlen?

3. Welke van de 3 varianten pijlen prefereert u? Waarom? (Slide 8,9 en 10)

4. Snapt u de betekenis van de gekleurde pijlen? (Slide 11,12 en 13)

5. Gekleurde pijlen vs. Zwarte pijlen.

6. Denkt u de pijlen nodig te hebben om sneller een solide diagnose te stellen?

B. Metaphorical alternatives in pilot

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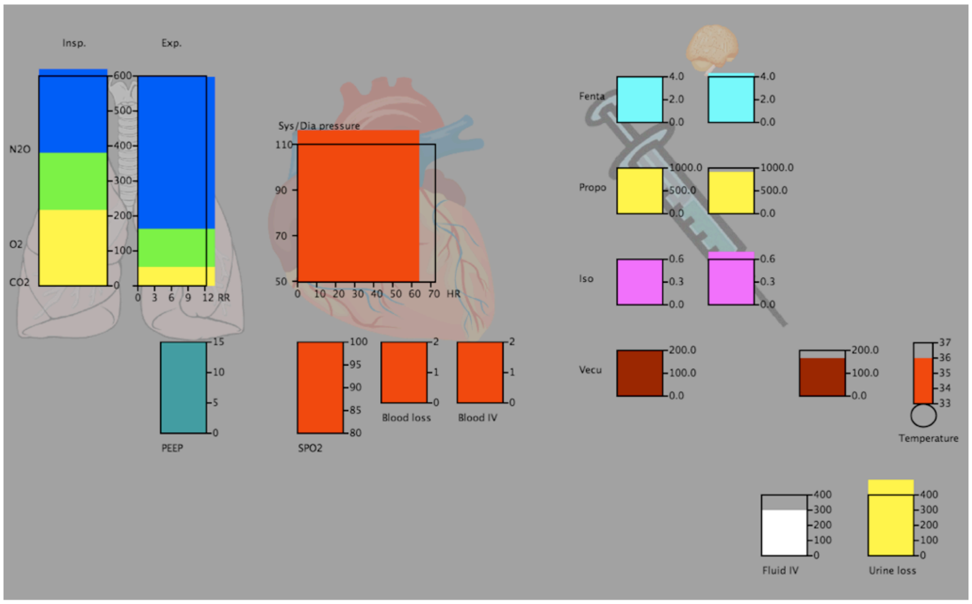

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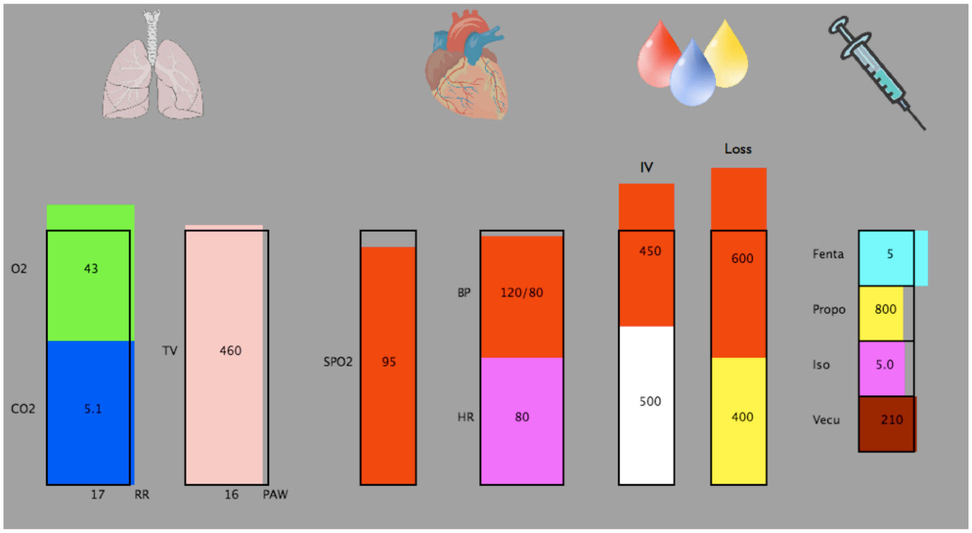
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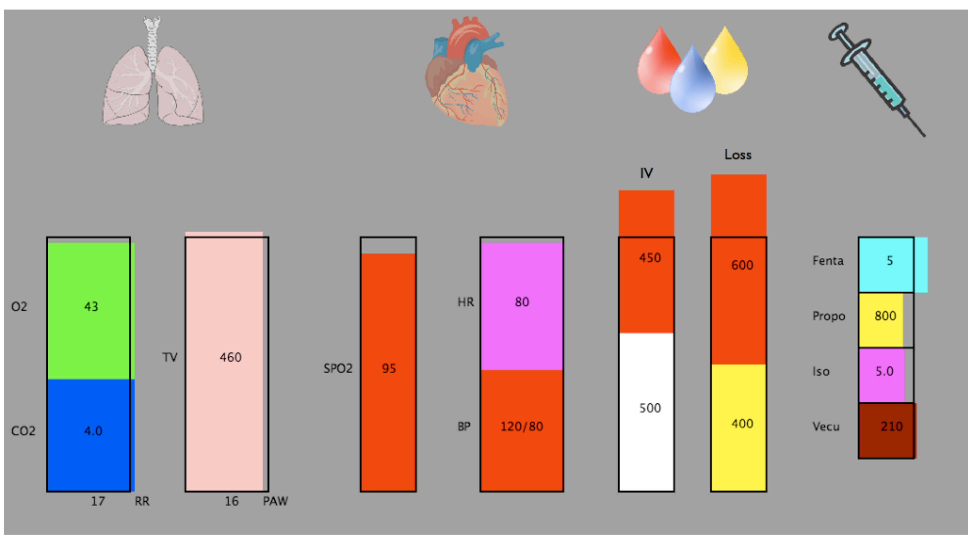
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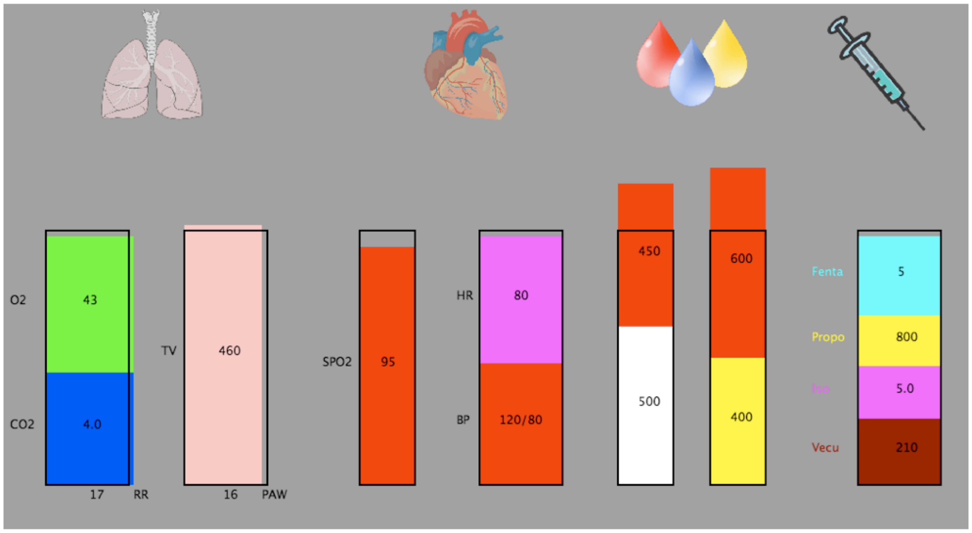
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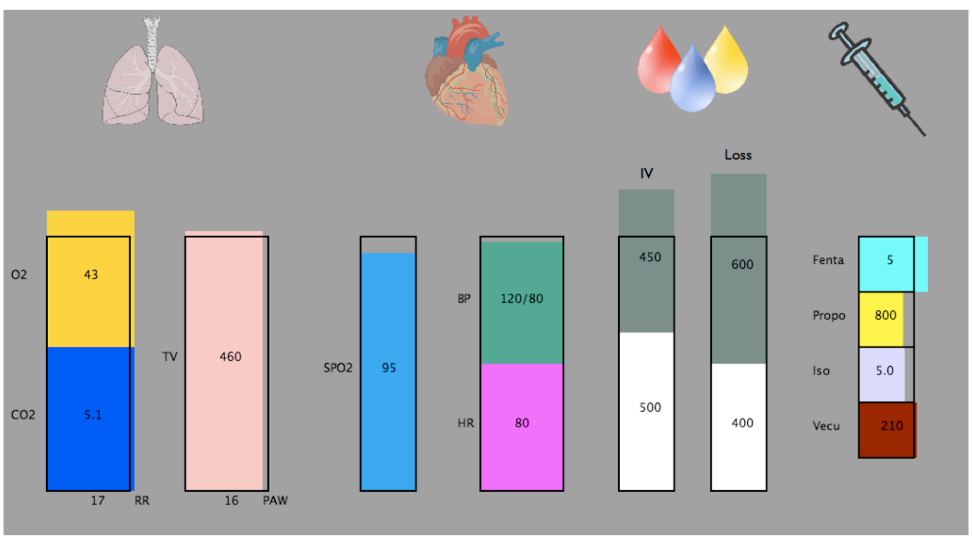
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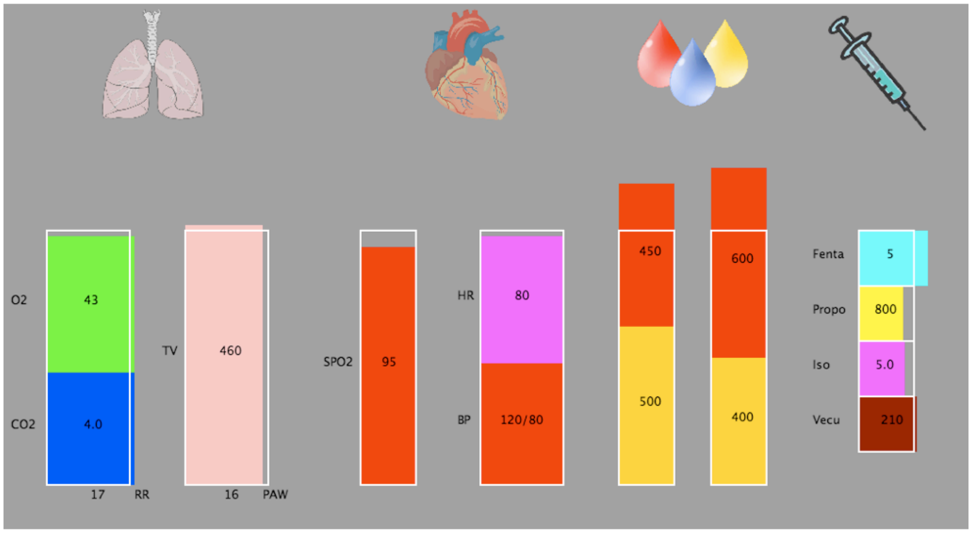

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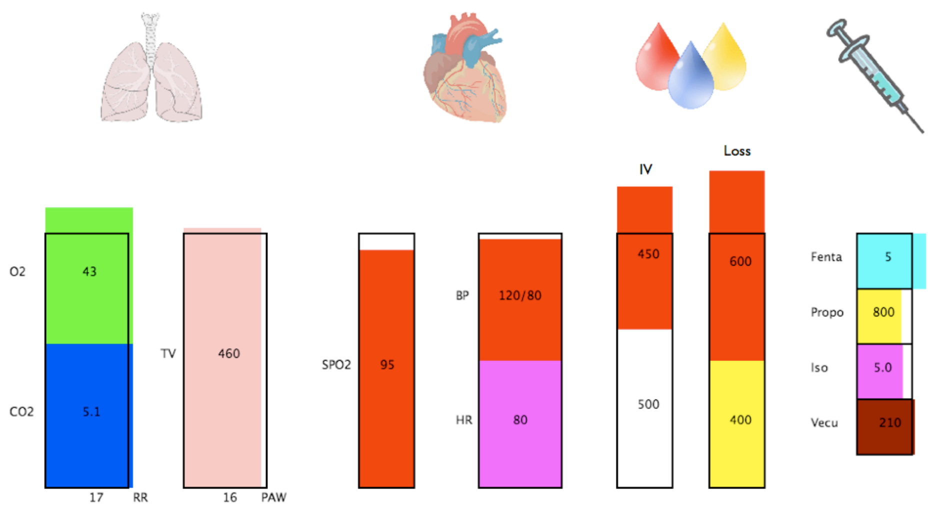

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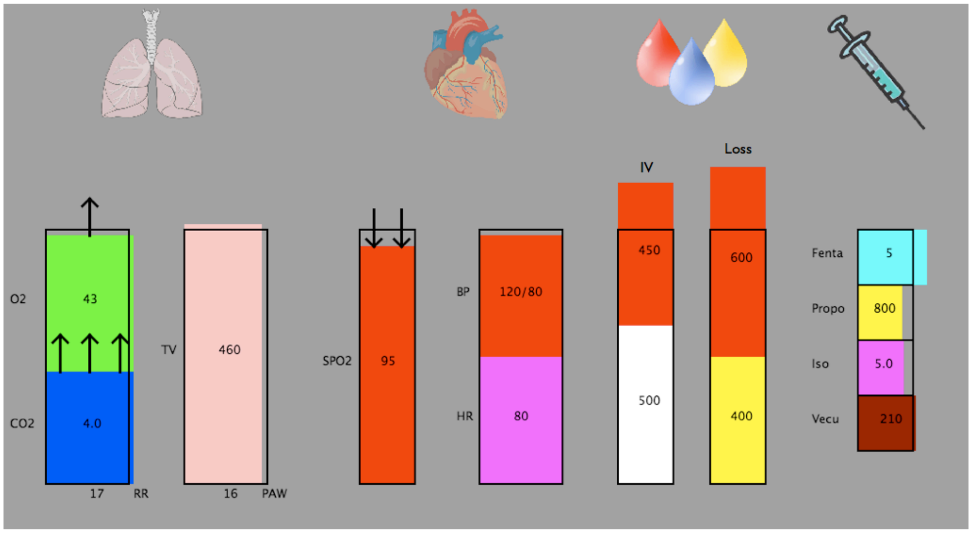

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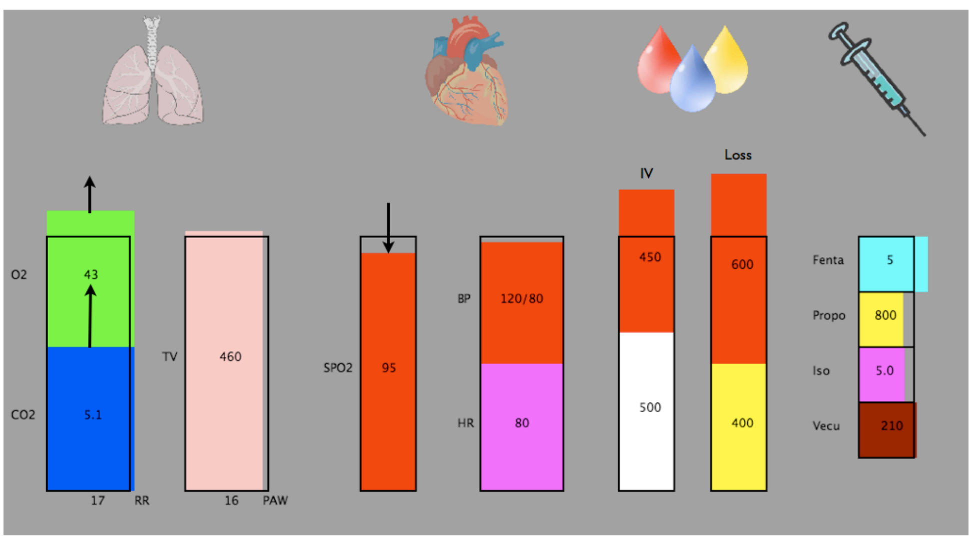

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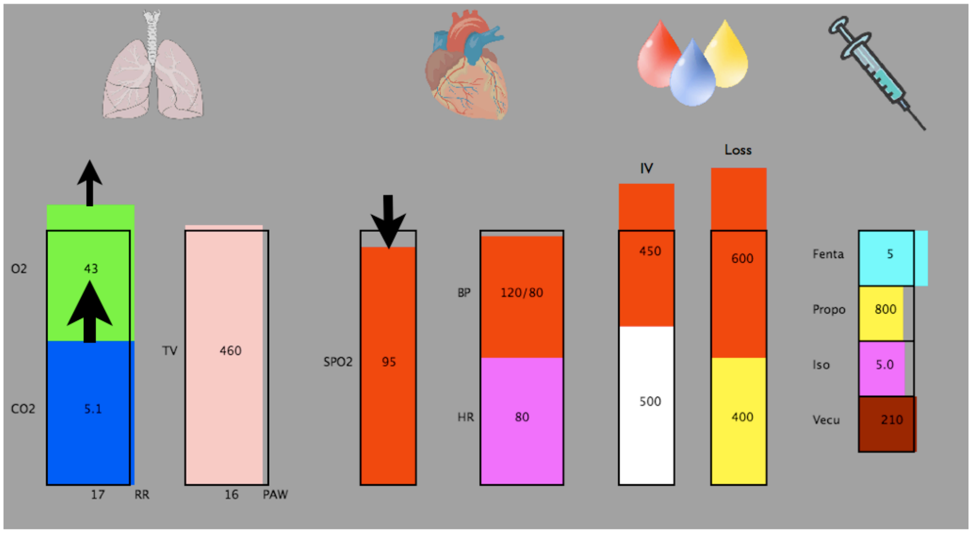
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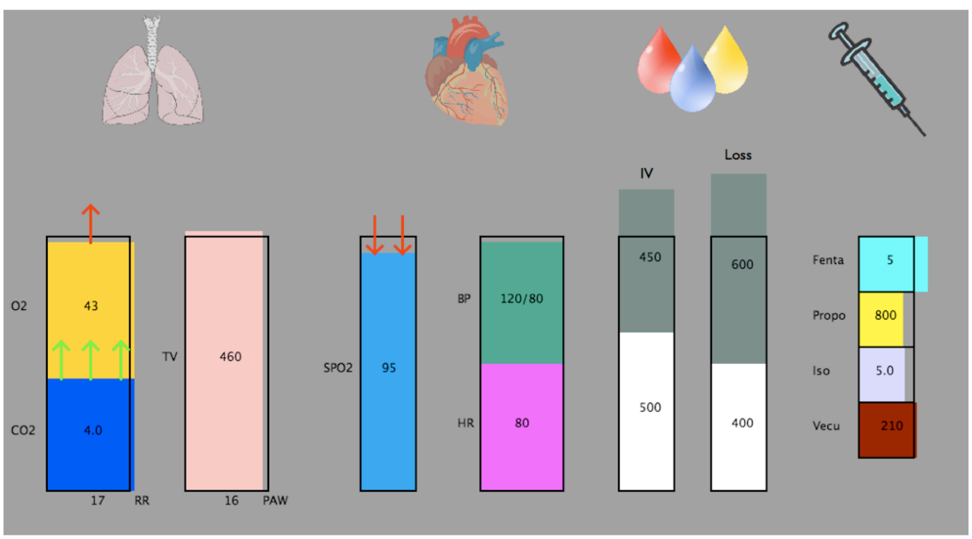
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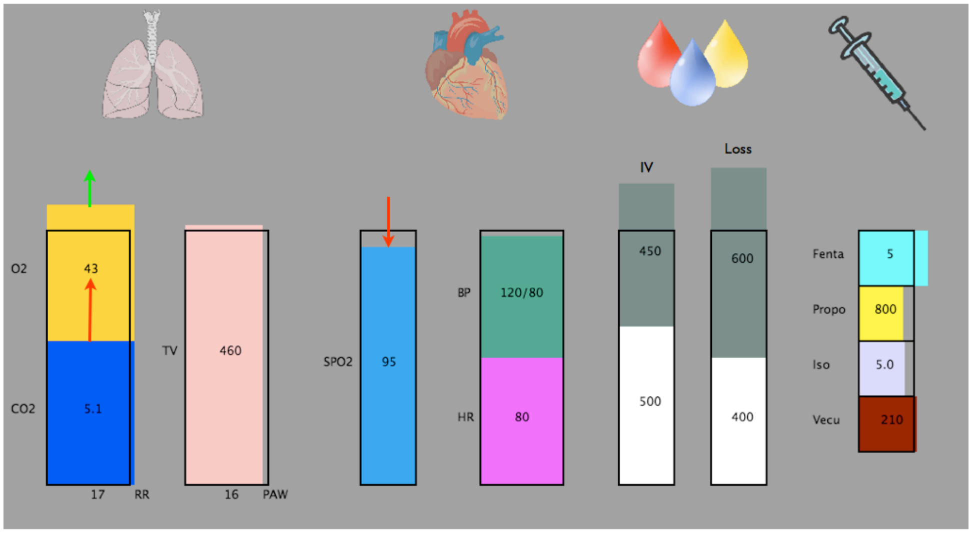
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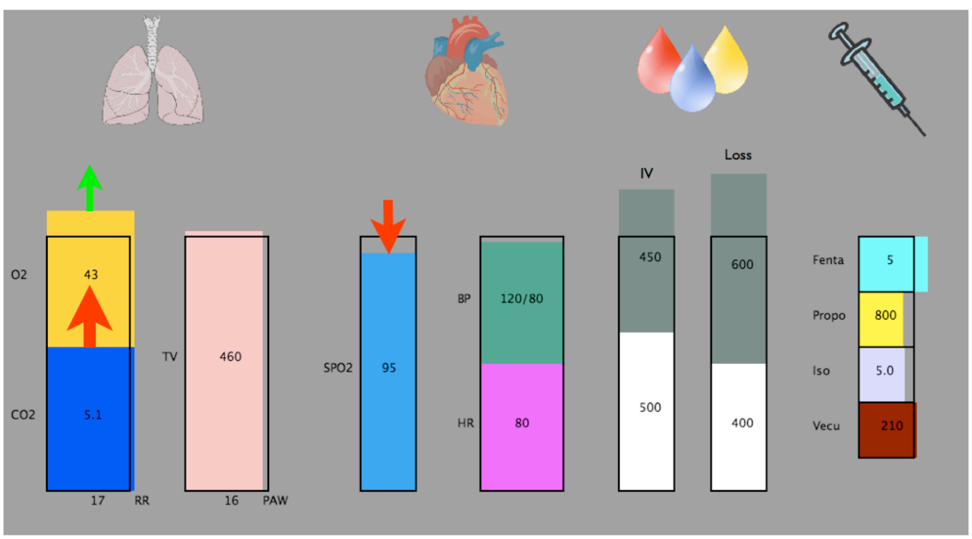
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C. Latin Square order of presented monitor types

Table C1. Latin square design for order of presented monitor types

Subject nr.	1st block	2nd block	3rd block	4th block	5th block
1	Classic	MAI	MAI + classic	tMAI	tMAI + classic
2	MAI	tMAI	Classic	MAI + classic	tMAI + classic
3	MAI + classic	Classic	tMAI	MAI	tMAI + classic
4	tMAI	MAI + classic	MAI	Classic	tMAI + classic
5	tMAI + classic	Classic	MAI	MAI + classic	tMAI
6	Classic	MAI + classic	tMAI + classic	MAI	tMAI
7	MAI	tMAI + classic	MAI + classic	Classic	tMAI
8	MAI + classic	MAI	Classic	tMAI + classic	tMAI
9	tMAI	tMAI + classic	Classic	MAI	MAI + classic
10	tMAI + classic	MAI	tMAI	Classic	MAI + classic
11	Classic	tMAI	MAI	tMAI + classic	MAI + classic
12	MAI	Classic	tMAI + classic	tMAI	MAI + classic
13	MAI + classic	tMAI	tMAI + classic	Classic	MAI
14	tMAI	Classic	MAI + classic	tMAI + classic	MAI
15	tMAI + classic	MAI + classic	Classic	tMAI	MAI
16	Classic	tMAI + classic	tMAI	MAI + classic	MAI
17	MAI	MAI + classic	tMAI	tMAI + classic	Classic
18	MAI + classic	tMAI + classic	MAI	tMAI	Classic
19	tMAI	MAI	tMAI + classic	MAI + classic	Classic
20	tMAI + classic	tMAI	MAI + classic	MAI	Classic

D. Trial in the experiment (dutch)

1.

2.

3.


Complicatie 1 / 11 Welke diagnose hoort hier volgens u bij?
Anafylaxie
Anesthesie diepte onvoldoende
Bradycardie
Diffusie stoornis
Fout in zuurstoftoevoer
Hypoventilatie
Luchtembolie
Spanningspneumothorax
Tachycardie bij sepsis
Ventilatiestop

4.


Complicatie 1 / 11
Klaar voor de volgende complicatie