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**Developing a System for Integrated
Automated Control of Multiple
Infusion Pumps**

The Multiplex Infusion System

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October 2013

Master Thesis

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Abstract

Most errors in ICUs are related to intravenous (IV) therapy. Previous studies suggested that hard to operate infusion pumps and the high cognitive workload for ICU nurses contribute to these errors. Conventional IV therapy requires separate lumens for incompatible IV drugs. This often requires the placement of additional catheters, which increases infection risk and physical discomfort for the patient.

In this thesis, a control system for multiple infusion pumps is proposed to reduce the problems with conventional IV therapy. The core idea behind this 'Multiplex infusion' system is reducing the number of required lumens by optimizing the number of IV drugs that are administered through a single lumen. A feasibility analysis showed that the Multiplex infusion system could significantly reduce the number of required lumens. A user interface for this system was designed with the goal of reducing the likelihood of errors by partially automating several tasks. In order to compare the usability of the new user interface with that of the conventional method of manually controlling multiple infusion pumps, a user based usability analysis was performed. Results indicated that the new user interface had an overall better usability and a significantly lower error rate.

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1 Introduction

There are various types of errors that can occur while operating medical devices. Among the most frequently occurring errors are device malfunction, malfunction of disposable parts and device setup errors. The causes of the first two types of error may result from poor design, faulty production or maintenance (Kohn, Corrigan, & Donaldson, 2000). The latter is often the result of human error, which may be caused by inadequate training, high workload and hard to operate devices (Kaye & Crowley, 2000). Among the most frequently used medical devices are infusion pumps. These pumps are used to deliver fluids into a patient's bloodstream in a controlled manner, with a predetermined volume or rate of administration. The errors that occur when operating an infusion pump may lead to a wrong dose of the fluid that is to be infused (Verkerke et al., 2011).

In an intensive care unit (ICU), patients typically receive intravenous (IV) therapy using multiple infusion pumps simultaneously, which are all controlled and monitored by a single ICU nurse. These nurses also need to continuously monitor the patients and monitor other equipment such as heart rate monitors, dialysis machines and feeding pumps. Obviously, the job of a nurse involves multitasking, which further increases the likelihood of human error (Back, Cox, & Brumby, 2012; Borst, Taatgen, & van Rijn, 2010). In such a hectic work environment with already vulnerable patients, this poses a serious safety threat for patients. Because many of these patients are heavily dependent on their medication, for maintaining blood pressure for example, interruptions or dosage errors can have severe consequences.

There are several problems with the current way in which intravenous therapy is administered. According to recent medication error reports, which have been gathered from multiple Dutch hospitals, 53% of all medication errors in the ICU are caused by errors in drug administration (Van Soest-Segers, Cheung, & Hunfeld, 2009). 40% of these administration errors were caused by an incorrect setup of an infusion pump, leading to an administration rate that is either too high or too low. 10% of all medication errors occurred in the preparation of the IV therapy, leading to events where the wrong drug or the wrong concentration of a drug was administered.

The incompatibility of infusion fluids is currently dealt with by administering incompatible fluids separately. In the hospital of the current study, patients in the ICU typically have a central venous catheter (CVC) which allows for three separated flows of infusion fluids to enter the bloodstream, known as a triple-lumen catheter. Often, the number of available lumens is too low for the number of incompatible infusion fluids. Therefore, there is often the need to place additional (peripheral) catheters, which causes physical discomfort for the patient and introduces additional infection risks (Evans et al., 2012; Hilton et al., 1988).

In the ICU in the current study, the multitude of infusion pumps increases the difficulty of the ICU nurse's job. Complaints have been made about the high number of maintenance, switching and monitoring actions that these pumps require. The ICU nurse also needs to be able to discriminate between up to twelve very similar pumps, often in a hectic environment. According to a study by Donchin et al. (1995) in an ICU, around 178 activities take place at the bedside of a patient per day and an average of 1.7 errors occur per patient per day.

Because of the high number of infusion lines that run from each infusion

pump to the patient's catheter often end up in a spaghetti-like tangle, which is unfortunately unavoidable (Raymer & Smith, 2007). Untangling these lines can be a very time-consuming business. Reducing this problem demands a reduction in the number of IV lines. This may be achieved by interconnecting multiple IV lines, allowing multiple drugs to flow through a single IV line. Due to the incompatibility of several drug pairs, nurses sometimes avoid this option although they are able to check which drugs are compatible and could be combined. Because of an expected further increase in the number of infusion pumps per patient, an increase of the current problems with IV therapy is also expected.

In this exploratory study we propose the "Multiplex infusion" system. This system acts as a control device for *multiple* infusion pumps at the same time. Instead of operating multiple devices separately, a nurse controls multiple pumps from a single user-interface. A smart control algorithm allows for multiple incompatible drugs (which currently would be administered separately) to be administered sequentially by separating them with a neutral fluid. This can be achieved by automatically switching between multiple infusion pumps sequentially. The control system optimizes the number of drugs that flow through a single IV line. As a result, the number of infusion lines can be reduced and with it the "spaghetti"-problem. Such a system also allows for the (partial) automation of several tasks, reducing the number of human actions and therefore the number of errors. Tasks that can be automated include setting up the infusion rate or flow rate, starting or stopping pumps and gradually increasing or decreasing the infusion rate.

The plan to build such a new infusion system was commissioned by the Intensive Care for Adults (ICV) of the University Medical Center Groningen (UMCG). Staff members of the ICV, both doctors and nurses, have reported problems with the current way in which intravenous treatment is administered. These problems lie in the usability of the current system, the complexity of the work environment and in the physical discomfort that patients experience as a result of the number of different catheters and IV lines. Plans for the construction of a new intensive care unit within three to five years and the integration of a new patient data management system (PDMS) offer the opportunity to radically revise the current IV system.

The goals of this study were to determine the demands for the Multiplex-infusion system and to assess which practical and technical challenges lie ahead before the system can be deployed safely. This thesis will focus on the medical-technical demands, as well as on the usability of the system. The physics, mechanics and all components of the proposed system will also be discussed in this thesis. A new graphical user-interface (GUI) will be presented and its usability was tested and compared with that of the user-interface of the current infusion system.

2 Objectives

In the previous chapter, I described various problems and disadvantages related to the current method of IV therapy. In this thesis, the *Multiplex infusion system* is proposed. It is a control system for multiple infusion pumps that could potentially reduce multiple problems related to IV therapy.

The overall goal of this study was to take the first steps in building a system which improves patient safety and has a better usability than the current IV system. The properties and limitations of this system also needed to be identified. In order to achieve this, two sub-goals were set:

The first goal of this study was to investigate whether or not the Multiplex infusion system has advantages over the current IV system, identifying these advantages and setting the demands for the system on a medical-technical level. In order to quantify such an advantage, I analyzed how much the number of lumens per patient could be reduced in a feasibility study. Decreasing the number of required lumens could improve patient safety and comfort. The expectation was that using Multiplex Infusion System would reduce the number of necessary lumens. In order to provide a good estimation of this number, I analyzed how IV lines and connectors were arranged for multiple ICU patients.

The second goal was developing a user interface for the Multiplex infusion system and comparing its usability with the use of multiple separate infusion pumps. The design of the new user interface was the result of an iterative process which involved the usability principles which will be discussed in chapter 4 and feedback from various nurses and physicians. The usability of the system was compared with that of the current system by measuring the time and button presses during the execution of several prototypical tasks. I hypothesized that the Multiplex infusion system would have a lower error rate than the current infusion system. I also expected that the differences in the numbers of clicks between both systems could be predicted by the number of clicks by an expert user, although I expected the actual number of clicks to be higher than this golden standard as a result of the variation between participants. I did not have a hypothesis on a difference in execution times. A questionnaire was administered in order to measure a subjective preference.

3 Practical Background

As one of the goals of this study was to develop a user-friendly control system for multiple infusion pumps in an intensive care unit (ICU), it is necessary to know more about the end users, their tasks and work environment. In section 3.1, I will provide a general description of the ICU and the tasks of the ICU nurse. Section 3.2 describes the concept of intravenous therapy and I will discuss the currently used infusion pumps in section 3.3. The definitions of the terms which are introduced in this chapter, can be found in Appendix A.

3.1 The intensive care unit

The ICU is a hospital department where care is given to patients with severe and life-threatening conditions. These are often vulnerable patients that require continuous monitoring by specially trained doctors and ICU nurses. The ICU is sometimes referred to as the critical care unit (CCU) or the intensive treatment unit (ITU).

3.1.1 The ICU at the UMCG

Within the University Medical Center Groningen (UMCG) there are several types of intensive care units, each with their own specialization. The current study was conducted at the intensive care for adults (Dutch: ICV). The ICV is the largest ICU in the Netherlands with 330 employees and a total of 53 beds, which are divided over four separate units. These are the Thorax Intensive Care (THIC), Surgical Intensive Care (CHIC), Neurosurgical Intensive Care (NCIC) and the Respiratory Intensive Care Unit (ICB). The ICU also has a mobile intensive care unit (MICU) which is used for the transportation of ICU patients. The UMCG also houses a pediatric ICU (PICU) and a neonatal ICU (NICU).

The current study was mainly conducted on the THIC and the CHIC of the UMCG. Although there are differences between the two units in the type of patients they typically accommodate, there is much overlap and collaboration between them. The THIC typically focuses on patients with conditions related to the thorax area, for example lung or heart transplant patients. The CHIC typically houses trauma patients, patients who have had surgery or patients with multi-organ failure. Both departments collaborate by exchanging nurses when understaffed or by taking over patients when one of the ICUs tends to get overcrowded. Both ICUs consist of a ward with multiple beds, which can be separated by a curtain. There are also separate rooms in order to isolate a patient when needed. At the left side of a typical ICU bed there is a docking station that can hold multiple syringe and volumetric pumps and a screen that will be used for the future patient data management system (PDMS). At the other side of the bed there is a monitor that displays the heart rate, oxygen levels and blood pressure. At the head of the bed there are often multiple feeding pumps. For some patients, there are additional machines used for respiratory support, dialysis or EEG measurements.

3.1.2 The tasks of the ICU nurse

The ICU nurse is responsible for the immediate care of one or two patients in the ICU, depending on the amount of care the patient requires. The tasks of the ICU nurse differ from those of a regular nurse as ICU nurses are more involved in the medical aspects of a patient's care which requires an additional 1.5 year educational program. Besides basic tasks like washing and grooming a patient, the ICU nurse monitors all medical devices surrounding the patient and has to adjust the medication accordingly. The ICU nurse is also in charge of the preparation and administration of medication and maintains a record of the patient's progress. In a daily deliberation with an intensivist (a physician specialized in ICU patients), interns and sometimes

other specialists such as a surgeon or a radiologist, the patient's progress is reviewed and treatment is adjusted accordingly.

3.2 Intravenous therapy

Intravenous therapy, or IV therapy, is the administration fluids through a vein. Infusion fluids can have several purposes, for example for restoring a fluid balance in the patient or as a carrier fluid for the administration of medication. IV therapy is the most common form of therapy in the ICU of this study. IV fluids are delivered by an infusion pump that is fitted with a syringe or infusion bag containing the fluid. The administration rate, which is mostly based on the type of IV fluid and the patient's weight, is programmed on the infusion pump. When a pump is started, IV fluid gradually flows through an IV line into the bloodstream of the patient.

3.2.1 Catheters

In order for IV fluids to enter the bloodstream, patients are fitted with an IV catheter. An IV catheter is a small flexible tube that is placed into a vein which allows an IV line to be connected. There are two main types of catheters. A peripheral catheter is placed in a peripheral vein is a single-lumen catheter, which means that it allows for a single stream of IV fluids. A central venous catheter (CVC) is placed in a central vein, which allows for the administration of IV fluids which are potentially damaging if they were administered peripherally. In the ICU in this study, almost every patient has a triple-lumen CVC, which means that three separated streams of IV fluid can enter the bloodstream simultaneously through the three separate passages in the tip of the catheter. This is very useful as there are several types of medication which are not compatible with each other, mixture could cause a precipitation reaction in the IV line or it could neutralize the effects of the IV fluids. Figure 1 shows the cross-sections of three types of catheters. Note that the diameter of the catheter generally increases with the number of lumens. As an average patient at this ICU receives seven different types of IV medication, there are often more incompatible infusion fluids than there are available lumens. Often additional catheters are required, which causes physical discomfort for the patient, adds to the number of IV lines that are required and increases the risks of catheter-related infections (Evans et al., 2012; Hilton et al., 1988; Mermel et al., 2001).



Figure 1: Cross-sections of a single, dual and a triple-lumen catheter.

3.2.2 Connectors

IV therapy requires various disposable components which are connectable to each other with *Luer-locks*. A Luer-lock is a standardized type of fitting that allows for a leak-free connection between a set of connectable components. I will refer to these components as *connectors*. Although catheters are part of the set of (disposable) connectors, they are generally not replaced unless there are signs that the catheter is not functioning properly or when it is believed that it has caused an infection. Other connectors which are used for IV therapy are syringes, IV lines and valves. Syringes are replaced after 24 hours or when they are empty. IV lines and valves are generally replaced after 4 days.

3.2.3 Tubing

In order to provide a clear description of all aspects of IV therapy it is necessary to provide a definition which encompasses the collection of connectors that are used in IV therapy and the way in which they are (inter)connected. I will refer to this as *tubing* and it is defined as follows:

Tubing refers to the complete configuration of connectors between all infusion pumps and all catheters in a patient receiving IV treatment.

For every patient receiving IV treatment, a tubing is arranged. A patient's tubing may be described in words, but it gets more complex to describe the connections of connectors as the number of infusion pumps increases. An example of a patient's tubing is depicted in Figure 2, where the tubing consists of multiple IV lines, a three-way valve and several connections. Although not depicted, the connection between the syringe on a syringe pump and an IV line is also part of the tubing.

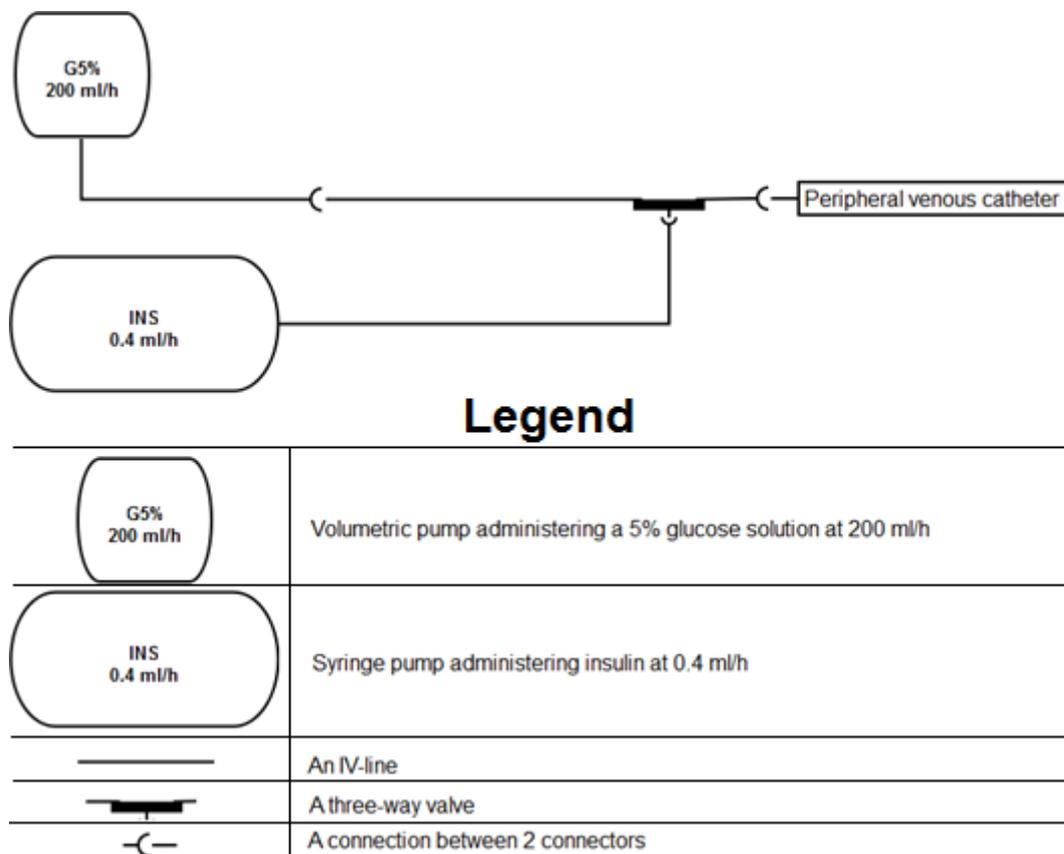


Figure 2: Example of the tubing of a patient receiving IV therapy. The catheter on the right side of this figure provides an entry point for intravenous medication into the bloodstream of the patient.

3.2.4 IV therapy related tasks

The IV therapy process consists of 5 main stages: *diagnosis*, *prescription*, *dispensing*, *administration* and *monitoring*. In the current study, dispensing, administration and monitoring are the most relevant stages as these actions are all performed by the ICU nurse who is the end user of the proposed control system.

In order to see how nurses dispense IV medication, a hierarchical task analysis (HTA) was performed of dispensing multiple IV fluids. The resulting HTA trees are depicted in Appendix C and the process will be discussed in the next section.

3.2.4.1 Dispensing

As many IV fluids are administered continuously, a common task for the ICU nurse is replacing an empty syringe or infusion bag. Infusion bags are pre-filled and do not require dissolving or mixing before the bag can be replaced. Replacing a syringe requires a 50 ml syringe to be prepared before it can be attached to a syringe pump. The process consists of three general stages: preparation, filling a syringe and verification by an additional nurse. The preparation stage consists of gathering all necessary equipment for filling the syringe, such as a diluent, a 50 ml syringe, and gloves. Labeling the syringe, so that the drug name and concentration are visible on the syringe, is also part of the preparation stage. How to fill a syringe depends on the way a drug is packaged. For example, insulin comes in 10 ml bottles and is dissolved in 40 ml of a glucose solution. Heparin is stored in 50 ml bottles, which does not require an additional diluent. An additional nurse compares the label on the original drug container with the label on the syringe in order to verify the contents of the syringe.

3.2.4.2 Administration

If the task is to replace a syringe, the current IV line needs to be traced from the pump up to the point where it is connected to the rest of the tubing. Most often, the IV line is connected to a valve, which is used to allow IV fluid from multiple IV lines to pass through or to block the flow from one or more IV lines. The pump is stopped and the valve is closed so that the old syringe can be disconnected. The new syringe is connected, the valve is opened and the pump is started again.

Some infusions should not be interrupted. For example, an interruption in the administration of noradrenalin may cause the blood pressure the patient to decrease. Therefore, when replacing an almost empty syringe of noradrenalin, a second pump is often used. The ICU nurse decreases the administration rate of the almost empty syringe stepwise, while stepwise increasing the administration rate of the new syringe. During this process, the nurse needs to monitor the patient's blood pressure and adjust the administration rate accordingly.

When a new IV fluid is prescribed, a compatibility matrix needs to be checked in order to determine how to arrange the tubing. The compatibility matrix that is used in the ICU can be found in Appendix E. If the new IV fluid is incompatible with the current IV fluids, it needs to be administered through a separate lumen, which may require placing an additional catheter. If the new IV fluid is compatible with one of the current IV fluids, they can be administered through the same lumen. After connecting the new syringe with IV fluid, the ICU nurse programs the prescribed administration rate on the infusion pump and starts the infusion.

3.2.4.3 Monitoring

Monitoring is required in order to review the patient's recovery rate and response to the administered IV fluids. In this stage, administration rates and frequencies may be re-evaluated and infusion pumps may be re-programmed accordingly.

3.3 Infusion Pumps

The UMCG owns and maintains about 2500 infusion pumps in total. There are two main types of infusion pumps: volumetric pumps and syringe pumps.

Volumetric pumps are used to deliver high volumes of IV fluids with moderate up to high administration rates (e.g. 5 to 999 ml/hour). IV fluids for volumetric pumps are contained in bags which are hung above the pump. An IV line runs from the IV bag, through the pump, which uses a peristaltic mechanism in order to control the administration rate.

Syringe pumps are mostly used for small up to moderately high administration rates (0.1-200 ml/h). Typically, a 50 ml syringe with IV fluids is loaded onto the pump. The pump gradually pushes the plunger of the syringe, thereby pushing the IV fluid outwards.

3.3.1 General functionality of an infusion pump

There are several manufacturers who produce infusion pumps. Although the designs may vary, the general functionality of infusion pumps is comparable. The most common operations with IV pumps are listed in Table 1.

Table 1: Common functionalities of infusion pumps and their description

Function	Description
Start / stop	Starting or stopping the administration of an IV fluid
Bolus	Rapidly administering large volume of IV fluid
Purge	Completely filling an IV line with IV fluid. Also known as flushing.
Set up administration rate	Setting the rate of administration of IV fluid (ml/h)
Titrate	Adjusting the administration rate without stopping the infusion
Volume to be infused (VTBI)	The user specifies the volume and time span in which an IV fluid needs to be administered. The pump stops when the programmed volume is administered

3.3.2 Alaris Asena GH Syringe Pump

At the ICV, the Alaris Asena GH Syringe Pump is the standard infusion pump. Figure 3 displays the layout of this pump. An average patient at this ICU receives IV therapy using seven of these pumps simultaneously, often combined with one or two volumetric pumps. The syringe pumps are placed in a stacked position using a docking station, which also provides power to the pumps. In case of transportation or a power failure, the pump contains a battery that can last about 5.5 hours.

The user provides input via the buttons on the pump. The pump provides visual feedback via a black and white display and the alarm indicator light. The display is used to display different menus corresponding to the different modes (e.g. continues infusion, purge, titration, bolus). During the default infusion mode, the display shows the current status, the administration rate, the total administered volume, an estimation of the time until the syringe is empty, a battery indicator and pressure measurements. During an alarm, a short alarm description is displayed. For example: “Low battery”. The blank buttons below the screen have different functions depending on the current mode. For example, during an alarm one of the blank buttons can be used to clear the alarm temporarily. During the default infusion mode, a the blank button grants access to the *bolus* menu, where administration rate of the bolus can be configured and the bolus can be started. Which function belongs to a blank button is displayed at the bottom of the screen, above the button. Audible output (sounding an alarm or when a button is pressed) is provided by means of a speaker at the back of the pump.

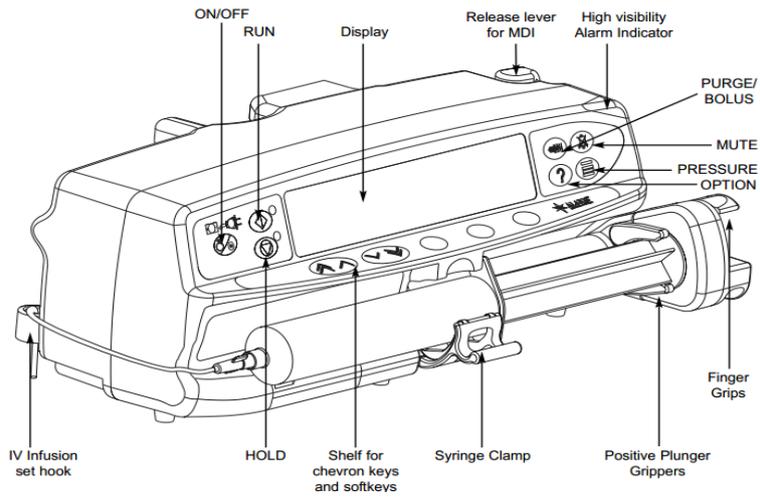


Figure 3: The layout of an Alaris Asena GW infusion pump. Image source: Tyler (2009).

4 Theoretical Background

Because low usability of infusion pumps is the major problem with the current IV pumps, this chapter will discuss different aspects related to usability. Usability is a common term in the field of human-computer interaction (HCI). HCI involves the study and design of the interaction between humans and computers. A well-designed user interface can provide an enjoyable and efficient interaction. I will start this chapter with discussing the types of user interfaces that are commonly used on infusion pumps. I will then introduce the term usability and how it can be analyzed. The types of human error that may result from poor usability will be discussed. Factors that may increase the likelihood of errors, such as multitasking and task interruptions, will also be addressed in this chapter.

4.1 User interface

A user interface (UI) is the space where there is interaction between a system and its user. Any component that is required by the user to provide input to the system and components which are used by the system to provide output to the user are part of the user interface. The user interface consists of all hardware and software components that are involved in the interaction between a human and a machine. Although there are many different types of user interfaces, I will only highlight two types of user interfaces that are relevant for this thesis.

4.1.1 Graphical user interface

A graphical user interface (GUI) is one of the most common types of user interfaces. This type of user interface accepts input via devices such as a keyboard or a mouse and provides graphical output to a screen or monitor. In the case of a fully integrated system such as an infusion pump, physical buttons are often used to provide input to the system and graphical output is commonly displayed on an LCD screen.

4.1.2 Touchscreen user interface

A touchscreen user interface is a specific type of GUI. On a touchscreen interface, the user provides input by touching the same screen on which the system provides its output. Because the displayed content can be changed dynamically, there are various ways in which users can provide input (e.g. button presses, tapping, pinching or sliding their fingers on the screen). The touchscreen user interface is a very versatile interface and it is used increasingly in various mobile devices as well as medical devices.

4.2 Usability

Usability refers to the extent in which a user can efficiently and enjoyably interact with a computer system. Nielsen (1994a) suggested that a system with good usability should meet the following five criteria:

- 1 *Learnability*: It is easy to learn how to work with the system.
- 2 *Efficiency*: When a user has learned to work with the system, a high level of productivity is achieved.
- 3 *Memorability*: It is easy to return to work with a system after a user has not used the system for a while. He or she should not need to learn to work with the system all over again.
- 4 *Low error rate*: The system has a low error rate. If an error occurs, it is easy to recover from it.

- 5 *Satisfaction*: The system is pleasant to use. Users like to work with the system and are satisfied when using it.

Although the definition of usability was originally intended for software engineering, the term could be applied any system where is interaction between a (human) user with a system, like a ticket dispenser or DVD-player.

4.2.1 Usability of infusion pumps

Although nurses in the ICU work with increasingly complex medical devices under hectic circumstances, relatively few studies have been carried out that aim at identifying ways to improve the usability of these devices. It is a well-known fact that many mistakes are made with intravenous medication. Among the possible errors with IV therapy are setting up a different administration rate than is prescribed, administering the wrong medication and not carrying out an order to change the medication or administration rate (Husch et al., 2005). In order to reduce the number of errors, manufacturers have tried to come up with user-friendly solutions. Attempts have been made to implement 'smart' infusion pumps which provide decision support and are able to warn medical staff when a certain dosage endangers a patient. However this did not succeed in reducing the number of medication errors (Carayon et al., 2005; Rothschild, Keohane, et al., 2005; Wetterneck et al., 2006). These smart pumps were programmed to alert their users when an administration rate exceeded ten times the suggested administration rate. According to a study by Husch et al. (2005), smart pumps were unlikely to prevent deviation errors in 97.3% of all cases where there was a deviation error. It is likely that most user inflicted deviations from the prescribed administration rate stay within the system's boundaries, while other deviation errors could not have been detected by the system because they were not related to the programming of the infusion pump, but may have been caused by preparing a solution of IV fluid in the wrong concentration.

There have been a few studies which compared the usability of different types of infusion pumps. Gagnon et al. (2004) performed a usability study on two types of infusion pumps. They found that there was a lack of feedback on the user's input and that menu structures were hard to navigate through. In a questionnaire among fifteen users of the Alaris Asena PK infusion pump, users indicated that the lack of feedback and hard-to-press buttons increased the likelihood of under- and overdosing (Davey, 2005). Heuristic analysis (Molich & Nielsen, 1990) on the usability of the user interface of an infusion pump in an intensive care unit identified 231 violations of the usability heuristics (Graham et al., 2004). Inconsistency in the design and the use of hard to understand language were the most common violations.

Only a few publications actually propose a redesigned user interface for an existing pump (Garmer, Liljegren, Osvalder, & Dahlman, 2000; Liljegren, Osvalder, & Dahlman, 2000). Current research on the usability of infusion pumps has been limited to the use of single pumps. In order to prevent errors with IV medication and improve the usability of infusion pumps effectively, pump manufacturers and researchers should study the interaction between the nurse and *multiple* infusion pumps in a clinical setting.

4.3 Human error

"The best people can make the worst mistakes - error is not the monopoly of an unfortunate few." (Reason, 2000).

When errors occur, poor motivation, negligence, inattention, repetition, forgetfulness or moral weakness of an individual is often seen as the principle cause of the error. This *person approach* (Reason, 2000), the tendency to blame an individual for an error, remains a widespread tradition in the medical field and elsewhere. Disciplinary measures, poster

campaigns, adding procedures on top of existing ones are some of the methods that are used to reduce unwanted human behavior. However, this approach does not succeed in effectively reducing the likelihood of errors. A system approach (Reason, 2000) assumes that one should expect human errors, even with the best people in the best organization. By assuming that we cannot change human behavior, but can change the conditions under which humans work, errors could be prevented more effectively. Reason (1990) defined errors as follows:

“Error will be taken a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some change agency.” (Reason, 1990).

For clarification purposes, Reason’s definition of human error will be decomposed into two parts. The first part speaks of a planned activity with some intended outcome. For example: Sending an e-mail to your neighbor, while you intended to send it to your mother is considered to be an error. The second part of the definition states that we do not speak of an error when some change in the environment is to blame for the adverse event. For example, a plane crash that is caused by a sudden wind shear is not an error.

Errors that occur due to negligence, poor maintenance or design flaws are called *latent errors* (Reason, 1990). Latent errors do not instantly lead to an adverse event, but they do increase the risk of an adverse event happening later on. For example, if a plane crashes because the maintenance crew has installed the wrong parts we speak of a latent error.

4.3.1 Types of human errors

Reason (1990) distinguishes three types of human errors: slips, lapses and mistakes. Slips and lapses occur when the action that is performed is not the action that was intended to be performed. The difference between a slip and a lapse is that the occurrence of a slip is observable and that of a lapse is not. For example: pressing the wrong button on some device is a slip. The action (and the result of this action) is observable. Not being able to recall something from your memory is a lapse. When a mistake occurs, an action proceeds as planned, but the action itself is the wrong action to achieve the desired outcome. Mistakes can occur when a situation is not assessed correctly, possibly due to the lack of expertise. This often happens in unfamiliar circumstances. Slips and lapses tend to occur during the performance of routine actions. Fatigue, stress and performing multiple activities are known to increase the likelihood of slips and lapses and mistakes (Moyen, Camiré, & Stelfox, 2008). The definitions of different kinds of errors are displayed in Table 2.

4.3.2 Adverse events

Although the consequences of many errors are not severe and errors often happen unnoticed, errors may lead to other errors with more severe consequences and should be prevented if possible. The term *adverse event* is used to describe an injury that is caused by a medical management. There is a distinction between adverse events and *preventable* adverse events. In *To Err is Human: Building a Safer Health System* (1999), this distinction is defined as follows:

“An adverse event is an injury caused by medical management rather than the underlying condition of the patient. An adverse event attributable to error is a “preventable adverse event.” (Burris, Brennan, Leape, & Laird, 1991; Kohn et al., 2000)

An example of an adverse event is when a patient who is not aware of any allergies, suffers from an allergic reaction to a drug. In this case there is no error causing the adverse event. In the case of a wound infection that is caused by a physician who ignored standard hygiene regulations, we

speak of a preventable adverse event (PAE). When an error occurs that does not result in any harm, we speak of a *near miss* (Moyen et al., 2008).

Table 2. Types of errors and their definition

Definition of errors	
Medication error	Any error in the medication process. (Moyen et al., 2008)
Slip	Failing to execute an intended action (Reason, 1990)
Lapse	Failing to execute an intended action due to a lapse in memory (Reason, 1990)
Mistake	Performing the wrong action for the desired outcome (Reason, 1990)
Near miss	An error that does not result in any harm (Moyen et al., 2008)

4.3.3 Medication errors

According to the estimates of the Institute of Medicine, between 44,000 and 98,000 Americans die each year as a result of medical errors, making it the 8th leading cause of death even by the lower estimate (Kohn et al., 2000). Mortality, prolonged hospitalization, (permanent) health damage, psychological impact on patients, family and caregivers and high costs are major consequences of medical errors (Moyen et al., 2008).

Medication errors are more common in the ICU than in any other hospital department (Kalisch & Aebersold, 2010; Moyen et al., 2008). As intravenous therapy is the most common way to administer medication, most medication errors are related to this form of therapy (Moyen et al., 2008; Tissot et al., 1999). Table 3 lists the errors that may occur during any stage of the IV process. Figure 4 displays the most common IV medication errors as they are reported by the British National Patient Safety Agency (2007). According to this report, 73.1% of all errors in the medication process occur during the administration and preparation stages.

Consequences of PAEs are often more severe with ICU patients than patients in other hospital departments, as they are often critically ill and therefore more vulnerable when errors occur (Giraud et al., 1993). According to a study in a French ICU, 19% of medication errors were considered to be life-threatening (Tissot et al., 1999). In a hectic and complex environment such as the ICU, the likelihood of preventable adverse events is twice as high compared to any other hospital department (Rothschild, Landrigan, et al., 2005). The most common cause of preventable adverse events in Dutch ICUs are administration rate related errors, of which 53% are directly related to the operation of infusion pumps (Van Soest-Segers et al., 2009).

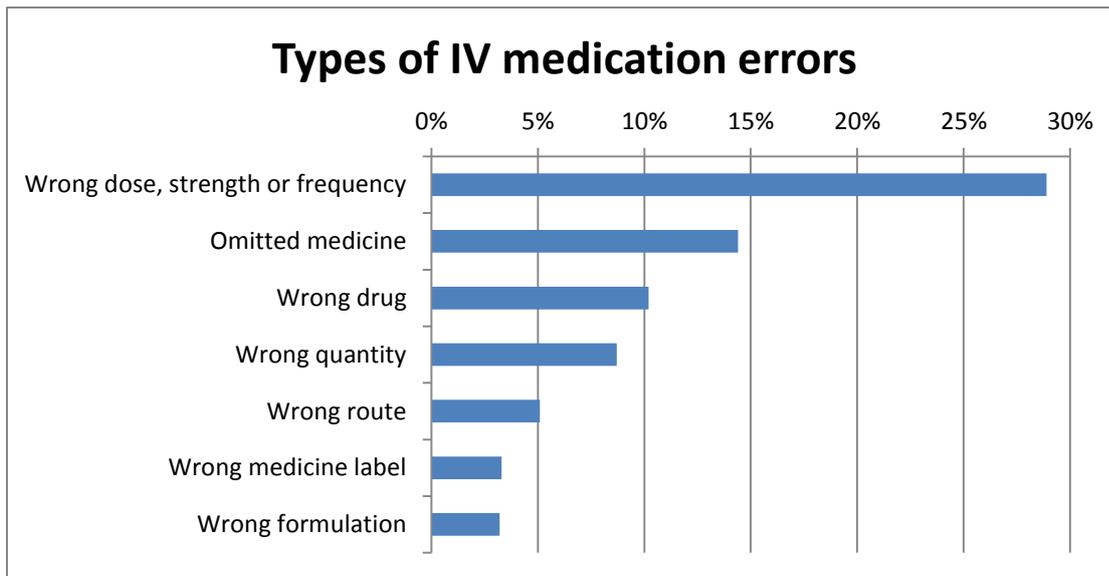


Figure 4: The division of frequent medication errors in percentages according to The National Patient Safety Agency (2007) from a total of 14,228 IV medication incidents.

The UMCG encourages its staff to report incidents, which may be done anonymously. Incidents may not always be reported due to time constraints, underestimation of the severity of the incident, embarrassment or due the fact that some errors occur unnoticed. In the ICU in the UMCG, 32% of the reported incidents in 2012 were related to the administration of medication. 60% of these incidents were attributed to human error. Among the most frequent errors in the IV medication process are programming the wrong administration rate and not administering the medication at all.

The actual error rates and types of errors that occur may be very different than the decentralized error reports suggest as some errors can be identified easier than others. For example: A faulty pump setup can be identified visually by comparing the administration rate on the infusion pump's display with the prescribed administration rate. Errors with drug concentrations are almost impossible to identify visually and are more likely to occur unnoticed.

4.3.4 Errors related to the IV medication process

There are several stages in the IV medication process and errors may occur in any of these stages. I will briefly summarize the general IV medication process.

1. *Diagnosis*: The patient's underlying condition is diagnosed based on the patient's symptoms and history. Although rare, mistakes can occur in this stage. For example: If a patient suffers from a condition that the physician has never encountered before, it is possible that the condition is not diagnosed correctly.
2. *Prescription*: Based on the diagnosis, a therapy is prescribed. Prescription errors may occur when the wrong type of medication or administration rate is ordered.
3. *Dispensing*: A drug is prepared by the pharmacy or a nurse based on the order by a physician. Preparation errors may occur when the order is misread, or when the wrong concentration or the wrong drug is prepared. The drug may also be dissolved in the wrong type of solution fluid, or may be dispensed too late.
4. *Administration*: A syringe or bag containing infusion fluid is attached to a syringe pump or volumetric pump, respectively. A nurse checks the compatibility of the added solution with other administered infusion fluids and decides which lumen will be used for administration. This routine step is vulnerable to slips. The compatibility can be misread or misinterpreted or the wrong lumen can be selected. As a consequence, incompatible drugs may be administered through the same lumen.

The next step in the administration stage is to program the desired administration rate and starting the pump. Here it is possible to program the wrong administration. It is also possible that the new administration rate is not confirmed by the used or that the pump is not started after confirming.

5. *Monitoring*: Monitoring is required in order to review the patient’s recovery rate and response to the administered drugs. In this stage, administration rates and frequencies may be re-evaluated. The occurrence of adverse drug events may also be noticed and appropriate actions can be taken in case of an ADE.

Table 3. Types of intravenous medication errors, the stage where they may occur and their description

Medication error	Stage of occurrence	Description
Administration rate difference	Administration	The administration rate that was programmed on the infusion pump differs from the administration rate that was prescribed
Incorrect concentration of IV fluid	Preparation	The concentration of the infusion fluid differs from the prescribed concentration
Incorrect IV fluid	Preparation or infusion pump setup	The administered IV fluid is different from the one that was prescribed
Combining incompatible IV fluids	Administration	Two or more incompatible infusion fluids are administered through the same lumen
IV line routing error	Administration	An infusion fluid is administered through a peripheral line while administration through a central line is preferred or vice versa
Delay in administration rate change	Administration	An order to change the administration rate was carried out one hour late or not at all
Unauthorized drug administration	Administration	A drug is administered that was not ordered
Prescription error	Prescription	An inappropriate drug or administration rate was prescribed
Diagnosis error	Diagnosis	The patient’s condition is incorrectly diagnosed
ADE response error	Monitoring	Failing to detect and respond to an adverse drug event

4.3.5 Preventing medication errors

The previous section illustrated that errors with intravenous medication are common in ICUs worldwide. In order to prevent medication errors, multiple studies have identified possible improvements to IV therapy and infusion pumps. As many errors occur during the setup of infusion pumps, Gagnon et al. (2004) evaluated the usability of multiple infusion pumps and suggested improvements for the user interface. According to a report by the Dutch Healthcare Inspection (Inspectie voor de Gezondheidszorg) the likelihood of intravenous medication errors increases due to the use of multiple different infusion pumps within the same hospital (Loekemeijer et al., 1997). Hospital-wide standardization of the types of infusion pumps to use could prevent these errors. However, as multiple hospital departments may have their own sets of demands regarding to functionalities on the pump, it may be inevitable for a hospital to own and use multiple types of pumps. Standardizing infusion pumps per department may be easier to achieve.

A study in a pediatric intensive care unit showed that a combination of standardizing drug concentrations, smart pumps and human-engineered medication labels reduced the number of reported errors by 73%. However it remained unclear if and by how much the smart infusion system contributed to the reduction of errors (Larsen, Parker, Cash, O'Connell, & Grant, 2005).

Melles, Freudenthal, de Ridder, & Snijders (2004) proposed the integration of information sources to build a support system for ICU nurses. As many electronic medical devices are essentially computers, it should be possible to extract information from them and build a system that collaborates with the nurse by giving personalized feedback, reminders and support through relevant checklists that correspond with the current situation. Laxmisan et al. (2006) also suggest such a support system for ICU nurses in order to reduce the memory load during multitasking. Although such a system sounds promising, there have been no reports of a practical implementation or experimental testing of such a system.

4.4 Multitasking

Multitasking is generally regarded as performing multiple tasks simultaneously. However, there is more than one type of multitasking. In this section, I will discriminate between two types of multitasking: concurrent multitasking and sequential multitasking (Salvucci & Taatgen, 2009).

4.4.1 Concurrent multitasking

Concurrent multitasking is performing two or more tasks at the same time (Salvucci & Taatgen, 2009). Some tasks, like walking and talking simultaneously, can be performed effortlessly without any interference. Other tasks, such as having a phone conversation while driving or talking to someone while writing a note, are almost impossible to do simultaneously. The reason is that these tasks require similar cognitive resources, such as memory, vision or manual operations. The more overlap there is in the required cognitive resources between the two tasks, the more interference there will be when trying to execute both tasks simultaneously (Wickens, 2008). The computational model of threaded cognition (Salvucci & Taatgen, 2008) offers a way to predict and explain multitasking performance by modeling the use of cognitive resources which are required for performing a task. In the threaded cognition model, a central executive control calls upon these resources when a task is performed. Although multiple resources may be called upon at once, a single resource can be assigned to one task at a time.

4.4.2 Sequential multitasking

In sequential multitasking, there is more time to switch between tasks (Salvucci & Taatgen, 2008). Often, a task may be performed for several minutes or even hours before a secondary task is introduced. Examples of sequential multitasking are writing a paper and reading a letter or cooking a meal and watching television. Sequential multitasking sometimes involves one task interrupting another, while maintaining a representation of the previous task in order to increase the likelihood that the first task will be completed. After completing the interrupting task, the primary task may be continued. An example of an interruption in the cooking and watching television task, may be an alarm indicating that the oven is pre-heated. The interruption task may require a dish to be placed in the oven and setting a timer. When this task is finished, one may continue watching television until the next interruption, for example when the dish is ready. How we are capable of returning to a previous goal can be explained by the goal-activation model (Altmann & Trafton, 2002).

4.4.3 The goal-activation model

Miller (1956) proposed the term *chunk* to describe how information is stored in our working memory. A chunk can be a single digit, a word of one or more syllables, a goal or some other type of grouped information. Miller found that humans are generally capable of storing between five and nine chunks in short-term (working) memory. In the goal-activation model (Altmann & Trafton, 2002), a chunk containing a goal is associated with an activation value, which decays

over time. A noisy threshold value, which consists of background noise from other goal chunks (distractors), determines whether or not the (target) chunk can be retrieved from memory (Figure 5). When the system tries to retrieve a chunk from memory, it will retrieve the most active chunk. Due to noise it is possible that a distractor is retrieved instead of the target goal chunk. If the activation of the target chunk is above the threshold value, it is more likely that it is retrieved successfully. If its activation is below the threshold, it is less likely to be retrieved. When a chunk is retrieved, its activation is increased. The more a chunk is rehearsed, the more likely it is that it can be retrieved from memory.

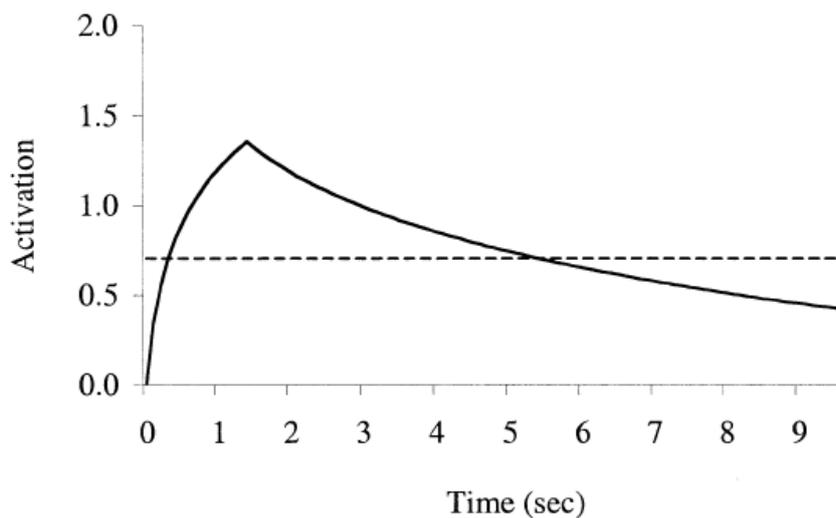


Figure 5 : From Altmann & Trafton (2002). The activation of a chunk over time. The dotted line represents a threshold above which the chunk can be retrieved from memory.

In sequential multitasking, there are multiple chunks in memory which represent the goals of the relevant tasks. Take, for example, task 1 and task 2 and their goals, goal 1 and goal 2. As task 1 is being performed, the chunk representing goal 1 gains in activation. As task 1 is interrupted by task 2, the chunk representing goal 2 is activated while the one representing goal 1 decays. This process is illustrated in Figure 6. When goal 2 is achieved, the goal-activation model attempts to retrieve goal 1, which increases the activation corresponding to goal 1, making it more likely that the goal will be retrieved from memory.

The threaded cognition model incorporates much of the goal-activation model, although modeling memory is only a part of the threaded cognition model. When an interruption is announced during a primary task, a problem representation of this task is rehearsed before starting the interruption task, increasing its likelihood to be retrieved from memory after the interrupting task is completed. The more time there is for this rehearsal, the more likely it is that the problem representation can be retrieved later on (Salvucci & Taatgen, 2008). If the interruption is not announced, there is no time to rehearse which makes it less likely that the problem representation of the primary task is retrieved.

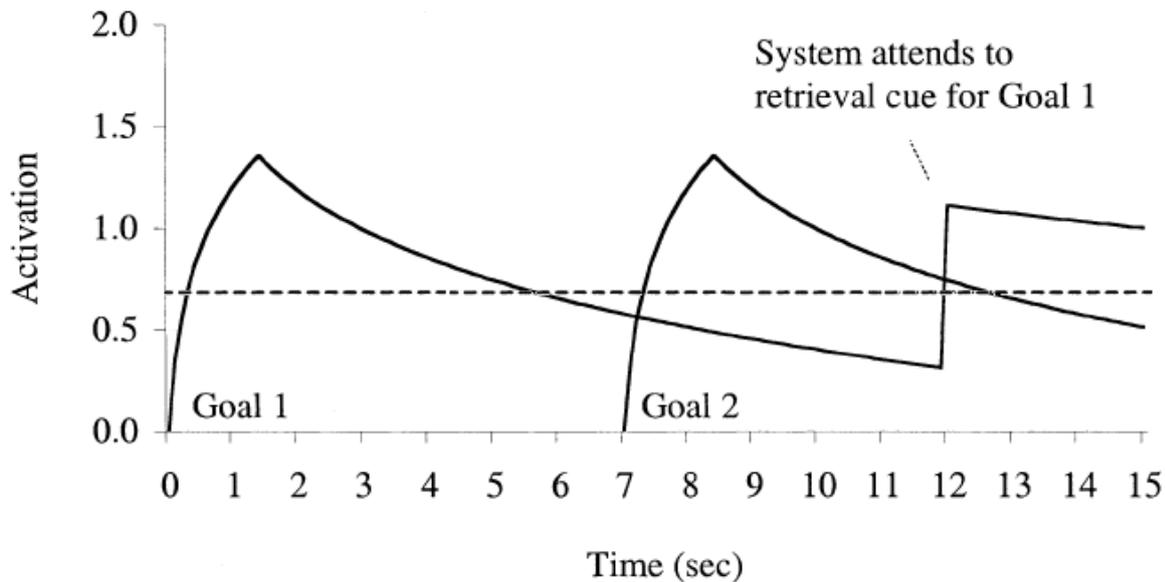


Figure 6: From Altmann & Trafton (2002). The activation levels of two chunks, representing the goals of two tasks. As one task is active, the activation of the corresponding chunk increases, while the other decays.

4.4.4 Multitasking and interruptions in the ICU

Both concurrent and serial multitasking are common parts of the job of the ICU nurse. For example: when starting or adjusting an infusion pump with noradrenaline, which affects blood pressure, a nurse needs to monitor a screen displaying the patient's blood pressure and set up the infusion pump at the same time. Nurses also need to remember upcoming appointments and other planned tasks, such as changing administration rates. Multitasking increases the cognitive workload of the clinician and nurses, which may result in a higher number of errors (Back et al., 2012; Borst et al., 2010; Coiera, Jayasuriya, Hardy, Bannan, & Thorpe, 2002).

In an ICU setting, interruptions can lead to errors. For example: when a nurse is interrupted by another nurse, a pager or phone call, the nurse may forget the task he or she was initially working on. This event may be explained by the models of goal-activation and threaded cognition (Altmann & Trafton, 2002; Salvucci & Taatgen, 2008). A nurse often has to remember multiple tasks at the same time, for example an upcoming appointment, monitoring a patient or personal errands. In a hectic work environment, it is possible that the maximal amount of the chunks that represent these tasks is reached. As an interruption occurs, the activation of a chunk corresponding to one of these tasks may decrease so much that it cannot be retrieved anymore. According to the goal-activation model it is also possible that other earlier goals (distractors) are retrieved instead of the target chunk (Altmann & Trafton, 2002). Interruptions have proven to be more disruptive as the mental workload (required processing capacity of the brain) increases (Salvucci & Bogunovich, 2010). Although multitasking and interruptions are common research topics in the field of psychology, only few studies focused on how multitasking affects the workflow and the frequency of errors in an ICU setting. In an observational study in the ICUs of two hospitals, 46 hours of concurrent multitasking, 1354 interruptions and 200 errors were documented (Kalisch & Aebbersold, 2010). In 46% of cases where nurses were administering medication they were interrupted. Although this study did not find a significant effect of interruptions on the error rate, it does illustrate the discontinuity in the workflow of the ICU nurse.

4.5 User-based usability evaluation

User-based usability evaluation is used to collect data from users as they interact with a system (Dumas, 2003). This data may be performance data or measures of user satisfaction. Performance

data, such as execution times or the number of errors, may be acquired by letting users perform several tasks with a system. This allows for an objective way to compare the performance and efficiency of multiple systems to each other. When combined with questionnaire data (rating scales) on user satisfaction, this type of usability evaluation is very useful when comparing multiple systems. If the tasks closely represent real-world tasks, results of this evaluation also allow to be generalized to the real world. A limitation of user-based usability evaluation is that performance data is less useful when only a single system is evaluated. As the aim of this study is to develop a new user interface which takes over the control of the current infusion system, a user-based usability evaluation is appropriate to evaluate the differences in usability of both systems.

4.6 Heuristic evaluation

A heuristic evaluation is an informal way to analyze the usability of user interfaces, using a set of guidelines (heuristics). Zhang, Johnson, Patel, Paige, & Kubose (2003) added the eight golden rules from Shneidermann (1998) to the heuristics from Molich and Nielsen (1990) in order to get a total of 14 usability heuristics for evaluating medical devices. A few examples of these heuristics are providing good error messages and giving informative feedback on the input of the user. In a heuristic evaluation, an evaluator is asked to point out usability problems in an interface as accurate as possible using the heuristics as guidelines. Although heuristic evaluation can be a valuable tool for usability analysis, preferably four or five evaluators should perform the same evaluation in order to be effective (Molich & Nielsen, 1990). For the heuristic evaluation of an infusion pump, all evaluators are required to have profound domain knowledge. Heuristic evaluation is also limited because it focuses on the execution of tasks in a controlled environment. Usability violations that are found, are not necessarily a problem for real users. As the complexity of a task increases, it tends to be more difficult to identify usability problems with heuristic analysis (Molich & Nielsen, 1990). Another limitation of heuristic evaluation is that it does not provide a solution to the usability problems it identifies. The aim of this study was not to improve usability of the infusion pumps that are currently used. Instead, the aim is to develop a new user interface which takes over the control of the current system of multiple infusion pumps. A user-based usability evaluation of a prototype is more appropriate for this goal.

4.7 Hierarchical task analysis

Hierarchical task analysis (HTA) is a way to decompose a task into smaller subtasks using a, hierarchical, tree-like structure (Stanton, 2006). An advantage of a HTA is that it allows analysis and comparison of the structures of complex tasks. In a HTA, tasks are decomposed into a main *goal* and one or more *sub-goals* that have to be performed in order to achieve that goal. These sub-goals may also consist of one or more sub-goals, depending of the amount of detail that is used in the HTA. A *plan* describes the order in which the sub-goals are performed, for example: "Perform action A and then action B, or perform action C".

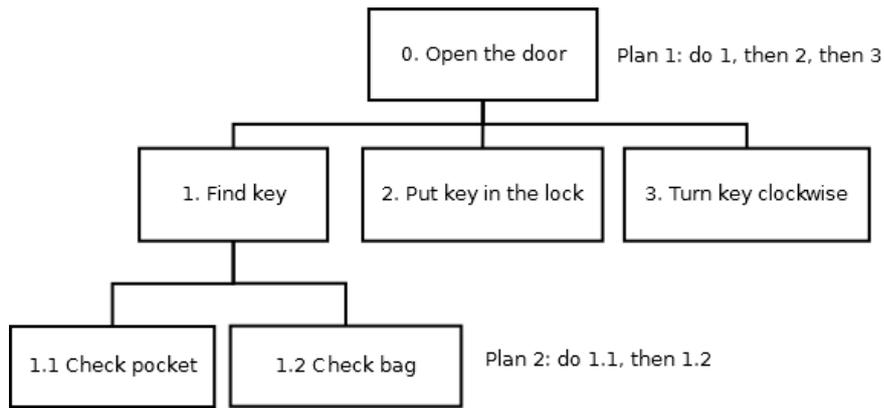


Figure 7: An example hierarchical task analysis tree of opening a door

Figure 7 shows an example of a hierarchical task analysis tree of opening a door. Plan 1 describes the steps to achieve the goal, which are completing steps 1, 2 and 3. Note that the hierarchy demands you to follow the tree structure in a depth-first fashion: In order to move on from step 1 to step 2, step 1 needs to be achieved by completing steps 1.1 and 1.2.

HTAs are very easy to construct and interpret. They are very useful for gaining insight in the structure of complex tasks. In this study, HTAs will be used to decompose and compare several tasks related to the intravenous medication process. These HTAs will be useful when comparing how various tasks are performed with both the current infusion system and the proposed control system.

5 The Multiplex Infusion System

In this chapter I will provide a theoretical description the proposed Multiplex Infusion System, which will act as an (automated) controlling device for multiple infusion pumps. First, I will provide a general description of the proposed system and its key features. I will then discuss the possible advantages of the Multiplex Infusion System over the current IV system. Next, I will discuss the design considerations and functionalities of the user interface in this chapter. Finally, I will describe the physics and chemical aspects of the proposed Multiplex Infusion System.

5.1 General description of the Multiplex infusion system

The idea for this system started out from the need to reduce the number of lumens that are required for administering incompatible drugs. The core idea behind Multiplex infusion is illustrated in Figure 8. By administering multiple incompatible drugs sequentially through a single lumen and separating these drugs by a neutral buffer fluid, the number of required lumens could be reduced. In other fields of research, this technique is called *multiplexing*. In order to achieve multiplexing behavior using multiple infusion pumps, a controller (human or computer) needs to switch between multiple pumps by starting and stopping them sequentially. As this would require many timed switching actions it is best to automate this process using a computerized control system.

Not all drugs are allowed to be interrupted during administration. Noradrenaline, for example, would still be administered through a separate lumen as an interruption in administration would cause an immediate decrease in blood pressure.

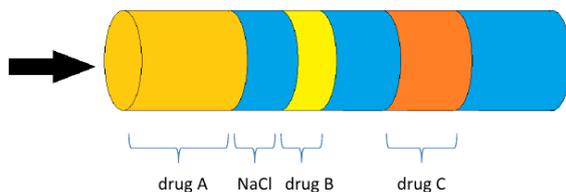


Figure 8: The core idea behind multiplex infusion. Incompatible drugs A, B and C are administered through a single lumen and separated by a neutral buffer fluid.

The Multiplex infusion system will require a user interface which provides a representation of the current set of infusion pumps together with the same control options as the current infusion pumps. As the ICV announces plans for the construction of a new intensive care unit and the upcoming integration of a new patient data management system (PDMS), this offers the possibility to radically revise the current IV system.

5.2 Key features

Since the Multiplex infusion system will be developed from the ground up, it allows for the incorporation of various additional features that could (partially) take over several tasks of the ICU nurse and help to prevent errors. The Multiplex Infusion System will have the following key features:

Control over all pumps from a single user interface: This bed-side platform will manage all the infusions for a patient. This includes control over volumetric and syringe pumps.

Multiple (incompatible) infusion fluids will be administered through a single lumen, separated by a neutral buffer fluid. Multiple infusion fluids would be administered pseudo-simultaneously, by rapidly alternating between pumps.

Incorporation of advanced administration profiles: At the ICU, many IV fluids are administered continuously. Once a syringe is empty, it needs to be replaced in order to maintain continuity. Some types of medication, like antibiotics, are administered in multiple sessions a day. Others may require a gradual increase or decrease in administration rate. These are all examples of *profiles*. A profile describes how a drug is administered in terms of time and administration rate. Only a few types of infusion pumps provide administration profiles, for example pumps with target controlled infusion (Davey, 2005). The multiplex infusion system would be able to administer drugs using various (complex) profiles, including profiles that require multiple pumps.

Incorporation of domain knowledge: By incorporating knowledge on compatibilities of drugs, the Multiplex infusion system would be able to guide the ICU nurse in arranging the IV tubing optimally. By connecting the Multiplex infusion system with the patient data management system (PDMS), orders for changes in administration rates could be fed to the infusion pumps automatically after a nurse confirmed the order at the bedside.

Integrated planning and control of alarms: Several planned tasks could be scheduled to be executed automatically. Instead of having multiple sources of alarms, alarm messages will be displayed on a single user interface.

5.3 Feasibility analysis

In order to assess whether or not multiplexing IV medication would reduce the number of required lumens in a clinical setting, a feasibility analysis was performed. The IV tubing arrangements of 12 randomly selected ICU beds were completely drawn out by two ICU nurses. Included in these schemes were all volumetric and syringe pumps, the types of medication and administration rate, the types and placement of all catheters and connectors. The nurses received a template to draw on, a set of instructions and a set of abbreviations to use when drawing the schemes. The template, used abbreviations and a legend can be found under Appendix D.

Drawing the schemes on the template was a stepwise procedure. The two nurses were instructed to start with denoting the used catheter types, in which vein and on which side of the body they were placed. The next step was to draw all infusion pumps in the order as they appeared, from top to bottom. The final step was to draw all IV lines and connectors which were part of the IV tubing.

All drawn schemes were analyzed in order to determine the number of currently used lumens for each patient. Digitalized versions of these schemes are attached in Appendix D. Based on the theoretical description of the Multiplex infusion system, the number of required lumens using the Multiplex infusion system was determined. In practical terms this meant that all IV fluids that were currently administered through a separate lumen, could be administered through the same lumen with the Multiplex infusion system. Exceptions were IV fluids that were not allowed to be interrupted, such as noradrenalin, adrenalin, dopamine and dobutamin. The results of this analysis are displayed in Table 4.

Table 4: Number of lumens currently used versus the number of lumens used with Multiplex infusion system

Bed number	Current number of used lumens	Number of lumens with Multiplex System
1	4	3
2	2	2
3	3	2
4	4	2
5	4	2
6	4	2
7	3	2
8	4	1
9	5	1
10	1	1
11	1	1
12	3	1
Average	3.17	1.67

There was a significant difference in the number of lumens between the current situation ($M=3.17$, $SD=1.27$) and with the Multiplex Infusion System ($M=1.67$, $SD=0.65$); $t(11) = 4.18$, $p = 0.002$. This result suggests that the number of required lumens can be reduced using the Multiplex infusion system.

5.4 Key advantages over the current IV system

Multiplex infusion system is expected to have multiple advantages over the current IV system. I will provide an overview of the most important possible advantages.

Reduction of lumens: As indicated in section 5.3, the Multiplex infusion system has the potential to decrease the number of required lumens by administering multiple incompatible drugs through a single lumen.

Reduction of catheter-related infections: As the number of required lumens can be reduced, less catheter insertions will be needed, thus reducing the likelihood of catheter-related infections.

Reduction of patient's discomfort: Catheter insertions are often painful and result in physical discomfort for the patient. By optimizing the number of required lumens and catheters, less catheter insertions would be needed.

Reduction of errors: By automating tasks which would normally involve manual actions from the ICU nurse, errors and preventable adverse events could be prevented.

Cost reduction: By reducing the likelihood of preventable adverse events, financial implications of dealing with these events could also be prevented or reduced. Depending on the severity of harm, additional costs can range from €382 up to €56,670.- euro per case (B Braun Melsungen, 2011). It is currently not possible to assess how many adverse events can be prevented.

By anticipating on future actions, the Multiplex Infusion System will have the potential reduce both the number and duration of sessions a nurse has to spend on physically configuring the infusion pumps. It is currently not possible to quantify this cost reduction.

Approximately 5% of IV fluids is currently spilled at the ICV because of the conventional method of replacing almost empty syringes. The Multiplex infusion system will have the potential to reduce the amount of unused infusion fluid by optimizing the use of IV fluids, by automatically switching to a new pump when the old syringe is completely empty. With an annual spending of €1.8 million on IV medication, automated switching could save €90,000 per year.

5.5 User interface

The Multiplex infusion system will have a touchscreen interface that will be placed at the bedside, proximal to the patient and the infusion pumps. Utilizing the currently available RS232-ports or through an infrared connection it is possible to control the current set of syringe pumps. In this project, I developed a user interface for the Multiplex infusion system. The usability heuristics from Molich & Nielsen (1990) and Nielsen (1994b) were applied during the development of the user interface together with consultation with multiple ICU nurses and physicians. Note that the user interface has not yet been implemented into a physical system. I will refer to several of the the following usability heuristics from Nielsen (1994a) as I discuss the design considerations of the user interface in the next section:

- Visibility of system status (1)
- Match between system and the real world (2)
- User control and freedom (3)
- Consistency and standards (4)
- Error prevention (5)
- Recognition rather than recall (6)
- Flexibility and efficiency of use (7)
- Aesthetic and minimalistic design (8)
- Help users recognize, diagnose, and recover from errors (9)
- Help and documentation (10)

5.5.1 Design considerations

The user interface needed to display all infusion pumps that were controlled by the system. For each pump, all relevant information regarding its current status needed to be visible immediately, which corresponds the first usability heuristic from Nielsen (1994a). ICU nurses and physicians indicated that information on the administration rate, the name and concentration of the currently administered drug, the remaining time before the syringe or infusion bag was empty and whether or not the pump was actually administering IV fluid were important to be displayed visually. Infusion pumps needed to be easy to distinguish from each other in order to prevent the wrong pump being selected (5). The user interface only needed to display information that was relevant to the current state of the system (1), which could contribute to a clear and minimalistic design (8).

Although automated control over multiple infusion pumps would be one of the main features of the Multiplex infusion system, the user interface still needed to allow its user to have basic control over the system, as suggested by the third usability heuristic. Therefore, the user should be able to start and stop the pump, to administer a bolus of IV drugs and to change the administration rate. I provided a detailed description of these features in chapter 3. The buttons that facilitated these features needed to be easily recognizable and preferably matched well-known real-world symbols (2). The *play* icon, which is universally used on television remotes and radios to indicate starting the playback of a movie or song, was chosen to indicate the *start* functionality on the user interface. Likewise, the *stop* icon was chosen to indicate stopping an infusion and the *fast-forward* icon was chosen to indicate the bolus functionality. As a user either

needed the start or the stop functionality, but never both at the same time, a single button was used that could represent either functionality; *stop* if the pump is running, *start* if the pump is not running.

The system needed to support the ICU nurse during error prone tasks which require completing multiple subtasks or manual actions which cannot be completed from a user interface. The replacement of an empty syringe, for example, takes multiple steps which involve physically connecting IV lines and opening valves. By featuring checklists during such tasks, a nurse will be able to verify each step of a real-world task on the user interface, which could prevent errors (5).

In order to prevent errors related to programming a wrong administration rate, the future Multiplex infusion system will be connected to a patient data management system, from which changes in administration rates can automatically be imported into the Multiplex system. An order to change an administration rate needs to be confirmed by a nurse on the user interface. An incoming order should be presented both visually and audible in order to be perceived by the nurse. The description of the order should be formulated clearly in order to be understood correctly.

5.5.2 Description of the user interface

Based on the design considerations in the previous section, a user interface was designed. A screenshot of the resulting user interface is displayed in Figure 9. Screenshots of all parts of the user interface can be found under Appendix F.

The user interface consists of three tabs: a main tab which displays all infusion pumps and pump controls, a tab where general patient and treatment information can be consulted, and a tab where the IV tubing is displayed.

The main tab contains panels which represent the currently used set of infusion pumps, the names of the administered IV drugs, administration rates, an image representing the remaining volume in the syringe and an estimate of the time until the syringe is empty. Additional information and features are available when a pump is clicked on. When clicked, the panel expands, displaying additional information and buttons for manually adjusting the administration rate, administering a bolus and stopping or starting the pump.

Planned changes in the IV treatment will be imported automatically into the Multiplex infusion system via a link with the PDMS. In case of an incoming order, the entire panel corresponding to the relevant pump turns *green* (Figure 9) and an audible beep is played. A short summary of the order is displayed on the right side of the pump panel. Clicking the pump panel starts a dialog asking for permission to change some parameter of the IV therapy, such as the administration rate. When a change in an administration rate is ordered, the nurse only needs to confirm this order at the bedside instead of changing the administration rate manually. By automatically entering the desired administration rate, administration rate errors can be prevented. When the task is to replace an empty syringe, a checklist can be used to verify the execution of important steps. The checklist is activated by default, but the user can choose to deactivate it. A user will be able to add a new infusion pump with a new drug via the upcoming PDMS.

In case of an alarm, the entire panel corresponding to the relevant pump turns *red* and an audible beep is played as is displayed in Figure 9. A short summary of the alarm is displayed on the right side of the pump panel. Clicking the pump panel starts a dialog with a description of the problem and suggestions how to solve the problem.

In order to change an administration rate manually, the relevant pump needs to be clicked on first, which then expands and enables the user to access the menu where the administration rate can be changed. Figure 11 displays this menu. After selecting and confirming the desired administration rate, the menu closes and the administration rate is changed.

The second tab, which is depicted in Figure 10, displays general information on the patient and which IV drugs are administered. This data will be imported from the future PDMS.

The third tab (Appendix F) displays the tubing for the IV therapy. This tab will be displayed when a new syringe or pump is attached. The system will guide the nurse in connecting the tubing efficiently based on knowledge on the compatibility of the administered IV drugs. However, as the current knowledge base on drug compatibilities is incomplete, this feature is not yet implemented in the user interface.

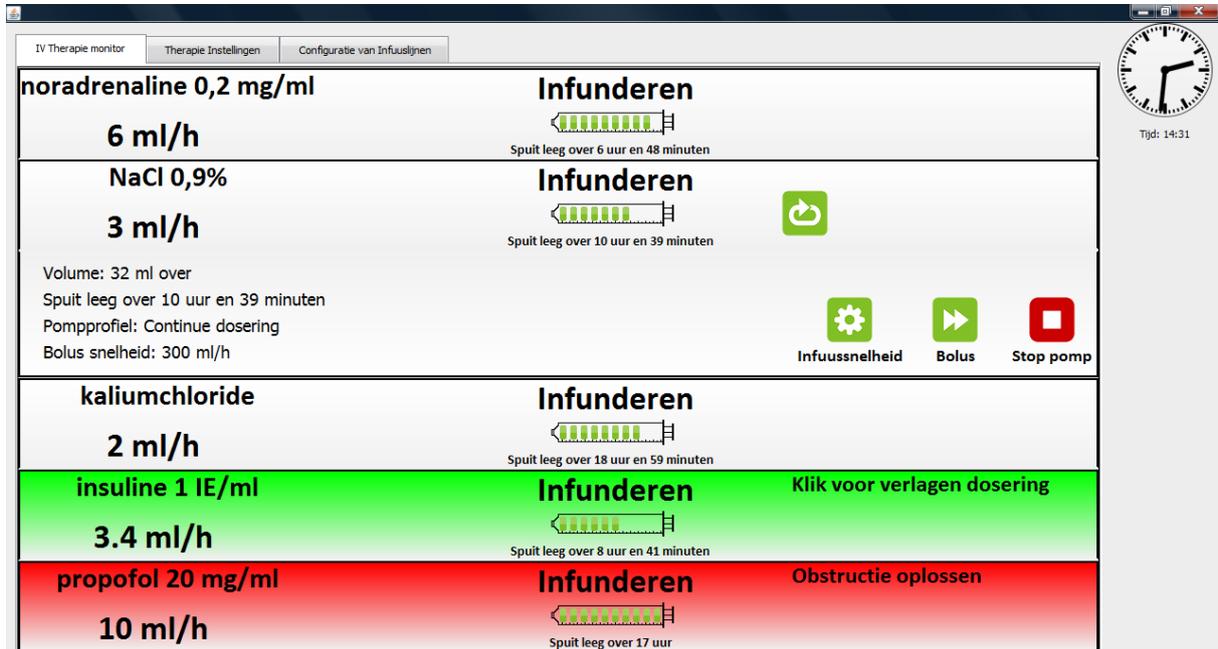


Figure 9: A screenshot of the main screen of the Multiplex user interface. Pumps are represented by panels, which expand and show additional information and features after being clicked on. In case of an alarm, the panel turns red. The panel turns green in case of an incoming order.

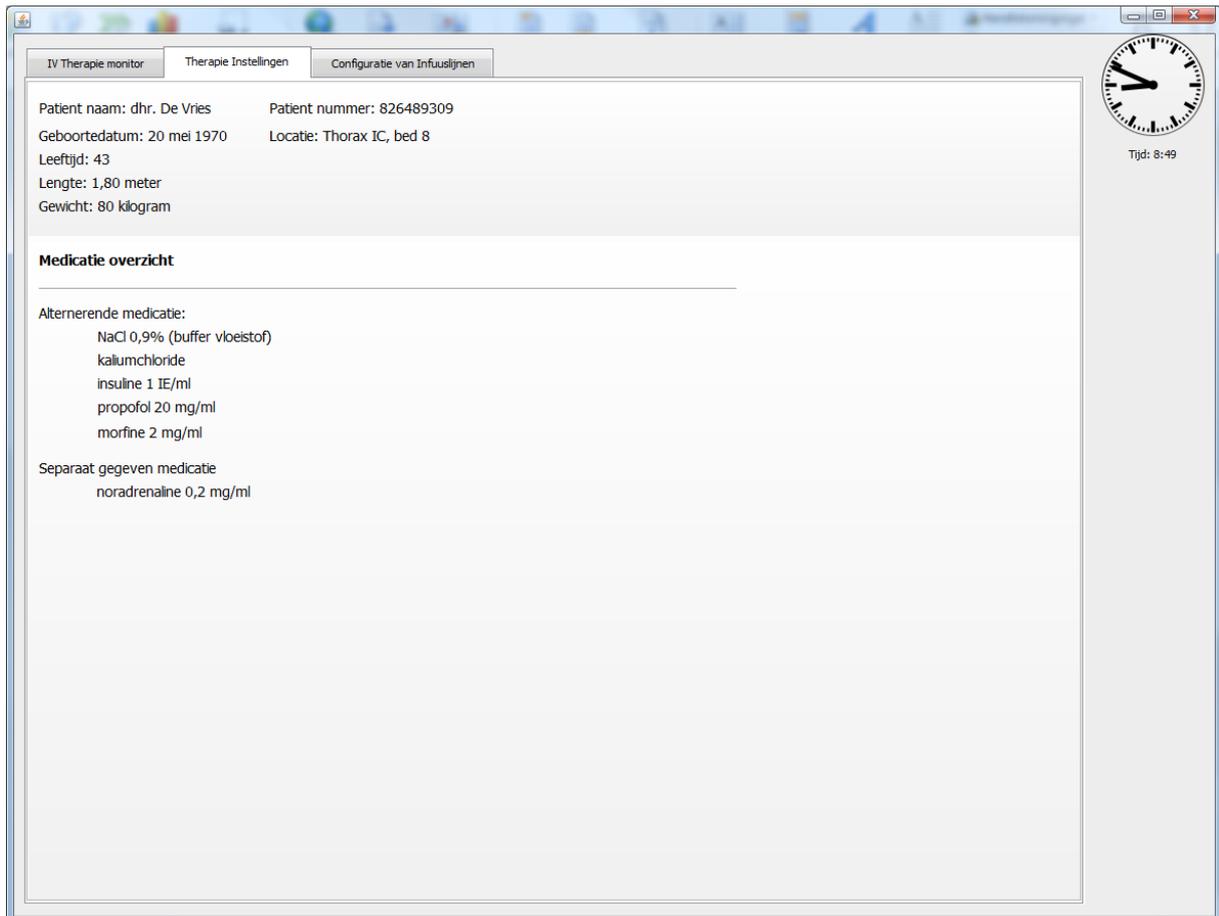


Figure 10: A screenshot of the second tab of the Multiplex user interface. This screen displays general information on the patient and provides an overview of the administered IV medication.

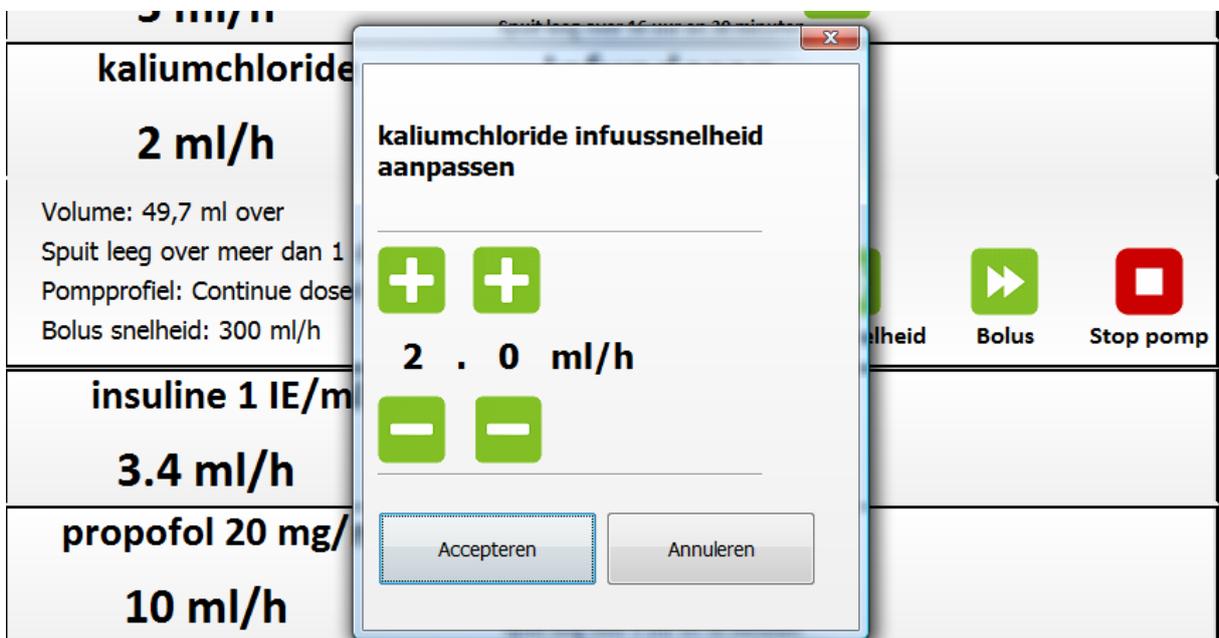


Figure 11: The dialog window for manually changing an administration rate. Pressing the “Accepteren”-button (accept) confirms the new administration rate. The “Annuleren”-button (cancel) is used to cancel changing the administration rate and closing the dialog window.

5.6 Quantitative physical and chemical understanding and modeling of flow and mixing in the Multiplex infusion system

Briefly, the essence of the Multiplex concept is fully integrated and centralized control of multiple infusion pumps. These pumps deliver infusion fluids through a tree-like network of IV lines to a single lumen that directly delivers the infusion fluid intravenously. The complete Multiplex concept involves full control of all deliveries of IV fluids to all lumens. The Multiplex infusion system will include an internal model that keeps track of all administered infusions. This model will also be used to schedule when, for how long and at which administration rate each IV fluid should be administered.

In order to describe and predict the physical and chemical aspects of Multiplex infusion it is important to provide a complete model of the physical behavior of the Multiplex infusion system. Therefore, this section will decompose the physical and chemical aspects of the Multiplex infusion system so that they can be modeled in a later stage of this project.

5.6.1 Infusion trees

Currently, most critically ill patients are treated with infusion systems that use one or more multi-lumen intravenous catheters. Each lumen is part of a separate *infusion tree*, which will be defined as follows:

An infusion tree is defined as one or more infusion pumps connected to a single lumen that is directly placed with its tip in a vein of a patient through a funneling arrangement of one-on-one connecting tubings and valves.

Figure 12 illustrates the principle of an infusion tree. As a single tree is physically isolated from other infusion trees, we only focus on the physical and chemical aspects of a single tree. Furthermore, a central concept of the proposed Multiplex infusion system is advanced control and the use of hardware that is commonly used in the ICU. Potentially useful devices such as electronically controlled valves or advanced injector systems are currently not part of the model as they are rarely used in the ICU. Therefore, the potential components of an infusion tree are:

- A syringe or volumetric infusion pump.
- A filled syringe
- A filled infusion bag
- An IV line.
- A 3-way valve or more-way valve
- A lumen of a single or multi-lumen infusion line.

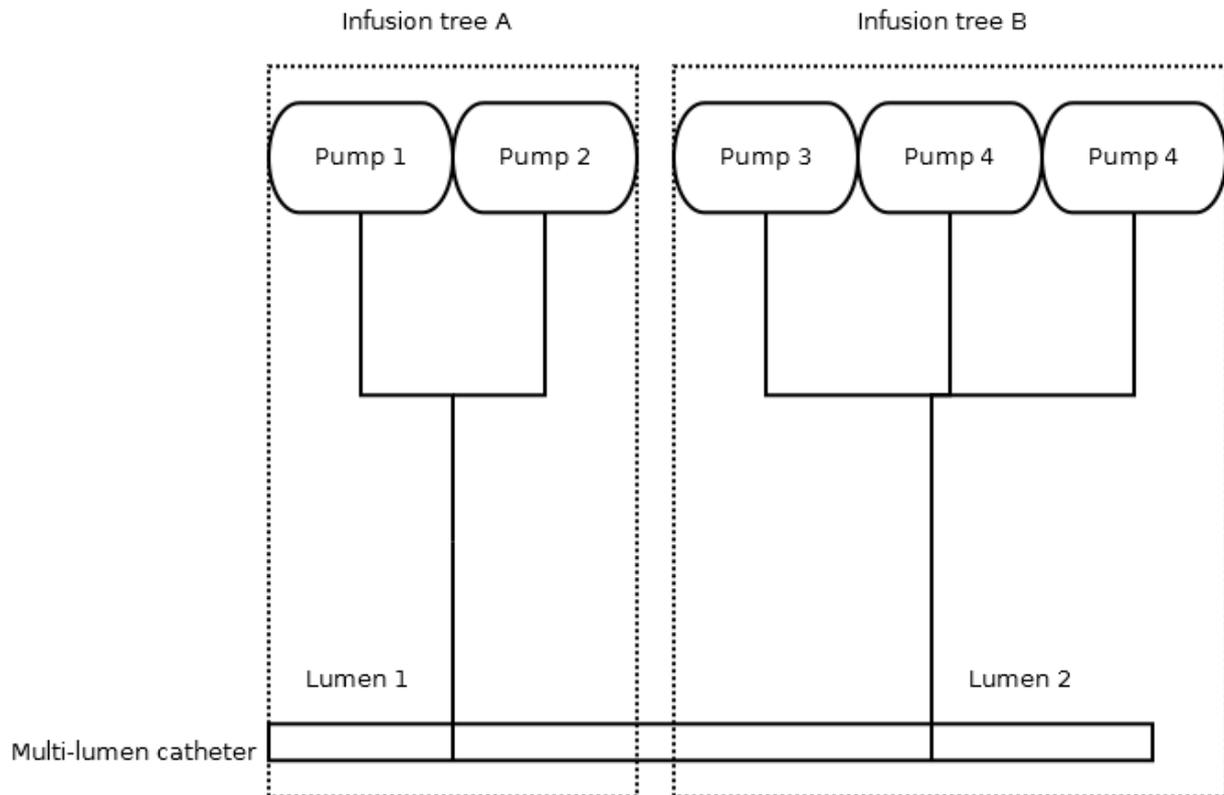


Figure 12: An example of two infusion trees. Although they are connected to the same catheter, pump 1 and 2 administer IV fluids through lumen 1, while pump 3 to 5 administer IV fluids through lumen 2. Pump 1 and 2 belong to infusion tree A and pumps 3 to 5 belong to infusion tree B.

Characteristics of the components that are relevant for modeling are:

Parameter	dimension
internal volume	[ml]
internal diameter(s)	[mm]
length(s)	[cm]
resistance(s)	[Pa·ml ⁻¹ ·h]
elasticity	[ml·Pa ⁻¹]

Secondary characteristics of components are: weight [g], cost[€], outer dimensions [cm³], material(s), opacity and valve positions.

5.6.2 Static description of an infusion tree

The static situation is described by the topological layout of these components as well as their individual characteristics. From each entry point in the tree, directly after a syringe pump or a volumetric pump, a minimal pathway to the exit point where the lumen of the intravenous catheter touches the bloodstream can be defined. Thus when 8 syringes are connected through a network to a single lumen, 8 such pathways are present. For each pathway a pathway length in [cm] volume in [ml], resistance [Pa·ml⁻¹·h] and elasticity [ml·Pa⁻¹] can be defined.

5.6.3 Dynamic aspects of an infusion tree

Dynamically speaking, the Multiplex infusion system may be in a *steady state* or a *non-steady state*. In a steady state, we have one or more non-zero flows that are all constant. Therefore, non-changing flows and pressures are expected theoretically. This assumes that infusion pumps are able to generate constant flows.

A non-steady state is a situation where one or more pumps are changing their infusion rates. Since the Multiplex system may sometimes change infusion rates every few minutes, a significant part of the total time the system is running, it may not be in steady state. Below I will try to define the distinction between a steady state and non-steady state more precisely in quantitative terms.

5.6.4 Dynamic aspects of an infusion tree under a steady state

The most important parameters of an infusion tree consisting of N pathways under dynamic steady state conditions are:

Cross section	[mm ²] Surface of a relevant complete cross section in the infusion tree
Flow ₁ through Flow _N	[ml·h ⁻¹] Flow through each pathway. Note that this flow is time-dependent, and may vary in the Multiplex infusion system
Flow _{tot}	[ml·h ⁻¹] Where Flow _{tot} =∑Flow _{1..N}
Flow _{any point}	[ml·h ⁻¹] Flow through any theoretically or practically relevant cross section in the infusion tree
Vol ₁ through Vol _N	[ml]
Vol _{tot}	[ml] Where Vol _{tot} < ∑Vol _{1..N} , since the individual volumes all contain the volume of the common final part the lumen of the venous catheter
P _{venous entry}	[Pa] Pressure at the point where the infusion fluid enters the blood stream. Thus P _{venous entry} will be expected to equal the CVP (central venous pressure) which is normally quite low compared to the other pressures.
P _{start main lumen}	[Pa]
P _{any point}	[Pa]

5.6.5 Dynamic aspects of an infusion tree under a non-steady state

The most important parameters of an infusion tree consisting of N pathways under dynamic steady state conditions are:

Infusion packet _{ID} (IP _{ID})	Small amount of a single infusion fluid, the minimal and central element of the Multiplex infusion concept
IP _{ID} -vol	[ml] Volume of an infusion packet
Packet-ID	A unique identifier (key) of an infusion packet, in order for the control system to keep track of this packet on its course from the infusion syringe or bag into the patient
ΔP _{pump N}	[Pa] Pressure variation resulting from pump itself
ΔFlow _N	[ml·h ⁻¹] Variation in flow resulting from the pump itself
Dispersion	Diffusion of the contents of a packet into neighboring packet

5.6.6 Chemical aspects

For all substances used, the Multiplex infusion system must know the maximally allowed concentration product [C_M]·[C_N], where C_M and C_N are known throughout the infusion tree. The assumption is that the concentration product within the infusion tree [C_M]·[C_N] is lower than the concentration product within the patient [C_{M patient}]·[C_{N patient}]. This combination is already acceptable in conventional IV therapy.

5.6.7 Integrating knowledge of the physical and chemical characteristics of the Multiplex infusion system

Integrating knowledge of the physical and chemical characteristics into the Multiplex Infusion System will be necessary to maximally understand what is happening within the system at any point in time. Based on a number of analytical equations as well as numerical simulation, the system ought to predict

- where in the infusion tree each individual infusion packet is at any time
- what the degree of dispersion is

For this purpose, knowledge of circulation, concentration and half-life of IV drugs is important. In many cases, two substances S_M and S_N do not interact, even in high concentrations. Such a situation corresponds with a green cell in the compatibility matrix (Appendix E).

When it is known that substances S_M and S_N do interact, the nature of this interaction can vary from inactivation of one or both substances, increased effectiveness of a drug, toxicity or precipitation reactions. When only inactivation occurs, the system could be set to allow the inactivation of a small percentage of the administered IV fluids.

6 Empirical study

One of the goals of this study was to develop a user interface with a better usability than that of the currently used setup of multiple infusion pumps. In the previous chapter, I presented a new user interface for the proposed Multiplex infusion system. In this chapter, I will discuss a user-based usability analysis where the usability of the new user interface was compared to that of the current method of manually operating multiple infusion pumps. The user-based usability analysis was performed using a computer simulation of multiple infusion pumps and a simulation of the Multiplex user interface.

6.1 Introduction

Previous studies indicated that usability problems are common with infusion pumps and they increase the likelihood of errors in intravenous therapy (Gagnon et al., 2004; Garmer et al., 2000; Graham et al., 2004). Studies on the usability of infusion pumps all focused on the user interface of a single pumps, although it is common for a patient in an ICU to receive treatment using multiple infusion pumps. In a hectic work environment such as the ICU, the likelihood of errors is higher than in any other hospital department (Kalisch & Aebersold, 2010; Moyon et al., 2008). Other studies suggested that a high cognitive workload and a high number of interruptions may contribute to these errors (Adamczyk & Bailey, 2004; Kalisch & Aebersold, 2010; Laxmisan et al., 2006).

In this study, a new user interface was designed for the Multiplex infusion system with the goal to have a better usability than the current method of manually operating multiple infusion pumps. In order to compare the usability of both user interfaces, a user-based usability analysis was performed using a computerized simulation. In an experiment, which featured both the Multiplex user interface and the manual operation of multiple simulated infusion pumps, ICU nurses performed multiple IV therapy-related tasks during two simulated days in the ICU (one simulated day for each user interface). During a single simulated ICU day, multiple different events occurred that required a certain task to be performed. For example: An alarm goes off indicating that an IV syringe is almost empty (the event). Therefore, the participant needs to replace the syringe (the task). During the experiment, clicks, response times, task execution times and errors were recorded in order to be able to measure participants' performance with each user interface. After completing two simulated days at the ICU, a digital usability questionnaire was administered.

Participants. Sixteen ICU nurses at the University Medical Center of Groningen (UMCG) participated in this experiment. Ages ranged between 29 and 58, the mean age was 42.3. Thirteen of the participants worked at the Thorax Intensive Care (THIC) and three worked at the Surgical Intensive Care (CHIC). Among the participants were 7 women and 9 men. The participants' work experience in the ICU ranged from 2 months until 31 years, with an average of 12.3 years. All participants signed an informed consent form before participating in the experiment.

Apparatus. A laptop running Windows Vista was used to run the experimental environment. A model was created in Java that simulates the behavior of multiple running infusion pumps over time, keeping track of syringe volumes at certain administration rates. On top of this model, two user interfaces were created using the Java Swing library. One represented 7 separate syringe pumps and the other represented the display of the Multiplex Infusion System. The separate pumps user interface was modeled after the Alaris Asena syringe pump and featured the same functionalities and menu structures. In order to display the user interfaces, an external monitor (resolution 1920 x 1080, 60Hz) was used in portrait mode. A keyboard and mouse were used to record input from the participants. All key presses and clicks were recorded so that they could be analyzed after the experiment.

Patient cases. For each user interface, a patient case and a set of 6 relevant drugs was created in consultation with an experienced ICU nurse. Two patient cases were created carefully, so that the difference between the used sets of drugs did not affect the execution of either of the task sets, nor created an unfair advantage when working with either user interface.

The Multiplex patient case was a 43-year old patient who had suffered a heart attack. The patient received noradrenalin, NaCl, potassium-chloride insulin, propofol and morphine. The separate pump case was an 18-year old patient who suffered from a subdural hematoma after a bike accident. This patient received noradrenalin, NaCl, nimotop, insulin, propofol and morphine.

6.2 Experimental events

Five different experimental events were created that needed to be dealt with by performing tasks that were common for the ICU nurse. The five events and a global task description corresponding to the event are listed in Table 5. Figure 14 to 18 display hierarchical task analyses (HTAs) of all five experimental tasks as they are performed using the Multiplex user interface and the separate pumps user interface in the experiment.

The *syringe empty* event is one of the most common events in the ICU and was therefore relevant to include in the experiment. When a syringe is almost empty, the pump where the syringe is connected to sounds an alarm. The ICU nurse then needs to stop the pump, replace the syringe and start the pump again in order to deal with this event.

The *NOR syringe empty* event may seem similar to the *syringe empty* event, but the task corresponding to this event can be quite different. Noradrenalin is a drug that influences the blood pressure of the patient and interrupting the administration of this drug could cause an instant drop in blood pressure. When a syringe of noradrenalin is empty, it is common for the ICU nurse to use a second infusion pump with a full syringe of noradrenalin. Some nurses gradually decrease the administration rate of the first pump while increasing the administration rate of the second pump until the desired administration rate is achieved. Others simply start the second pump at the desired administration rate and stop the first pump simultaneously. There are also nurses who rapidly replace the almost empty syringe without using a second pump. This is sometimes done when the administration rate is low enough to be interrupted without a noticeable change in blood pressure. The *NOR syringe empty* event is included in the experiment as the required task can be complex and may include many steps depending on the strategy that the participant chooses. When noradrenalin is administered, the Multiplex infusion system will guide its user into using a second pump, after which the system decreases the administration rate of the first pump stepwise, while increasing the administration rate of the new pump. As this task execution is very different from the conventional operation of multiple pumps, it is important to include this task in the experiment.

The *change in administration rate* event is also a task that illustrates the difference between the Multiplex user interface and that of manually operating multiple infusion pumps. In the real-world version of this task, a physician orders a change in administration rate during the daily multidisciplinary consultation after which the ICU nurse changes the administration rate on the pump. Using the Multiplex infusion system, an order to change the administration rate will automatically show up on the user interface after which the nurse only has to confirm the suggested change.

The *interruption* event was designed to test whether or not the participant is able to complete a set of subsequent tasks while being interrupted by a phone call. The event starts with an order to change an administration rate. Shortly after the incoming order, a phone rings which has to be answered. The experimenter then asks the participant to find out how long it takes until a certain syringe is empty. During this question, an obstruction alarm goes off. After answering the question, the participant can continue completing the tasks. The goal-activation model that I discussed in chapter 4, would predict that an interruption would increase the likelihood that (a part of) the task would be neglected due to the decay of the corresponding goal chunk in memory

(Altmann & Trafton, 2002). I expected that, as orders in the Multiplex user interface remain visible on screen, this would remind the ICU nurse to complete the task after the interruption. Using the separate IV pumps, the nurse will not be reminded that a task is not completed. I therefore expected more errors will occur using the separate pumps than with the Multiplex user interface in this task.

In order to prevent the participant from anticipating on an interruption, the *obstruction* event was designed as an alternative to the interruption task. Both the interruption task and the obstruction task occurred only once in the experiment, while the other tasks occurred twice (once using each user interface).

Table 5: The 5 experimental events and a global task description corresponding to the event

Event name	Event description	Task
Syringe empty	Alarm indicates that syringe is almost empty	Replace empty syringe
NOR syringe empty	Alarm indicates that noradrenalin syringe is almost empty	Replace empty syringe of noradrenalin.
Change administration rate	Incoming order to change an administration rate	Change the administration rate of a pump
Interruption event	- Order to change an administration rate - “Phone call” interruption - Obstruction in Pump	- Read the order - Answer a question regarding one of the pumps during phone call - Change the administration rate as ordered - Solve the obstruction
Obstruction	Obstruction in pump	Solve the obstruction

6.3 Experimental conditions

The experimental tasks were performed using two simulated user interfaces, which were displayed on a monitor in portrait mode. There were two conditions in the experiment, the *Multiplex* condition involved the use of the Multiplex user interface that I discussed in chapter 5. The *separate pumps* condition involved controlling multiple separate pumps and its design and menu structure was based on the currently used Alaris Asena syringe pumps. A screenshot of the *separate pumps* interface is displayed in Figure 13. As all experimental tasks were performed on a computer, real-world actions such as replacing a syringe, connecting or untangling an IV line were also simulated.

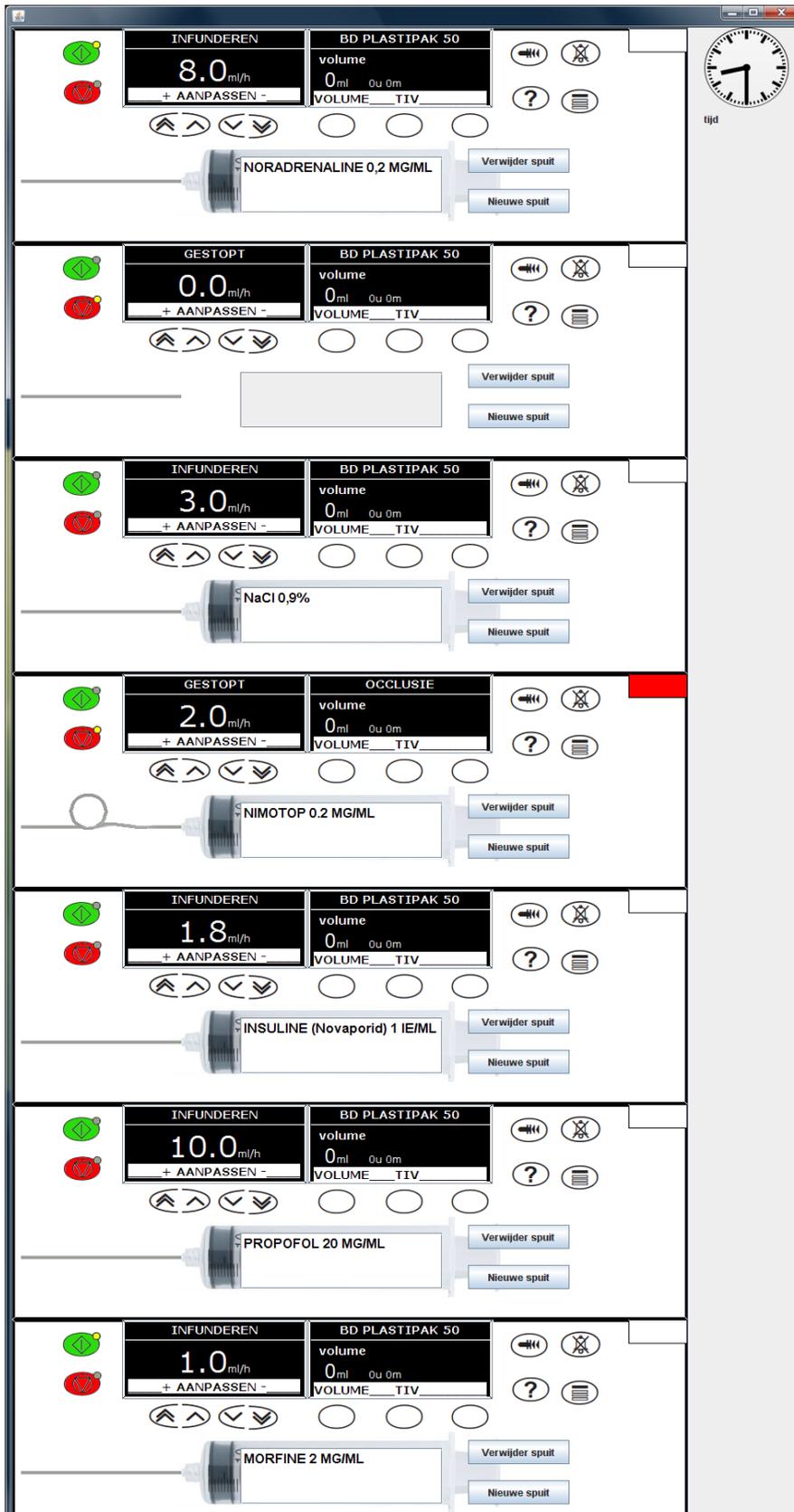


Figure 13: Screenshot of the interface for the “Separate pumps” interface. The pump administering nimotop (center) displays an occlusion alarm due to an obstruction. The obstructed IV line can be untangled by clicking on it.

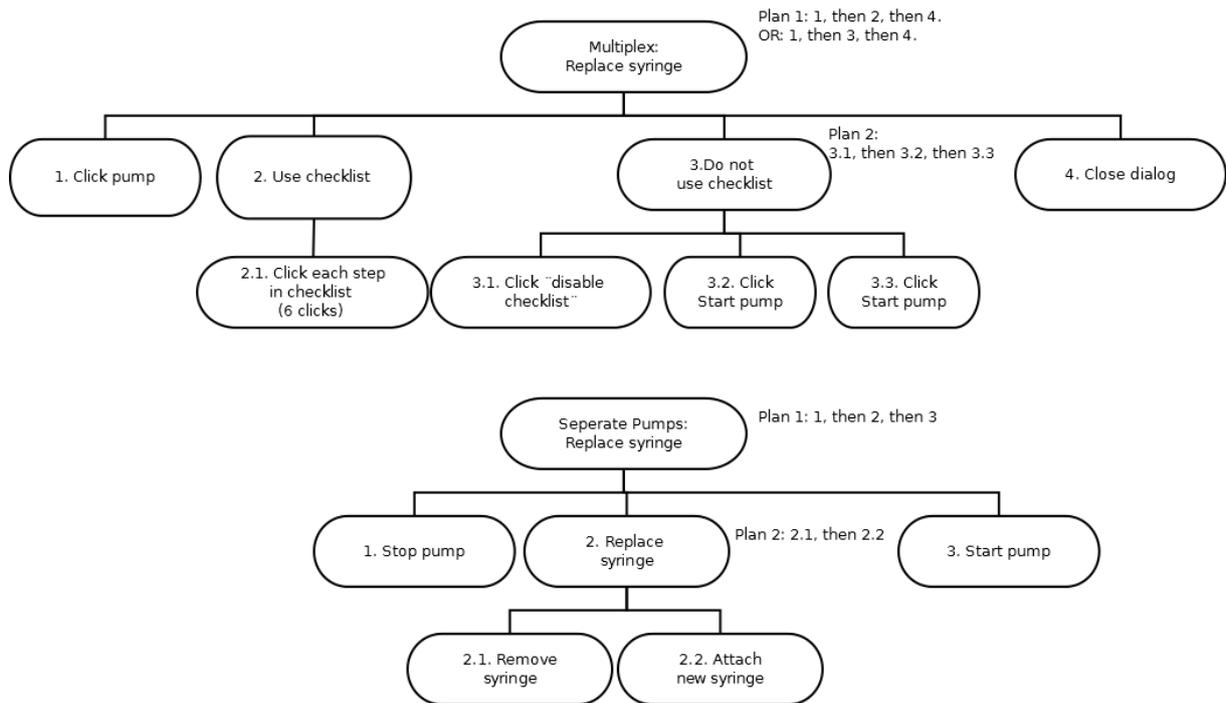


Figure 14: Hierarchical task analyses of replacing an empty syringe using the Multiplex user interface (top) and the separate pump interface (bottom).



Figure 15: Hierarchical task analyses of replacing an empty syringe of noradrenalin using the Multiplex user interface (top) and the separate pump interface (bottom).

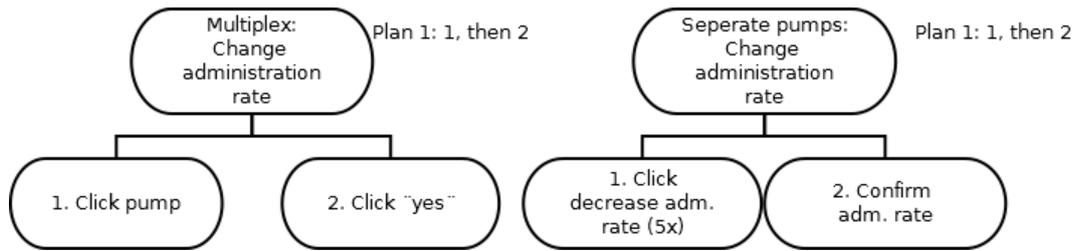


Figure 16: Hierarchical task analyses for the *change administration rate* task using the Multiplex user interface (left) and the seperate pumps interface (right).

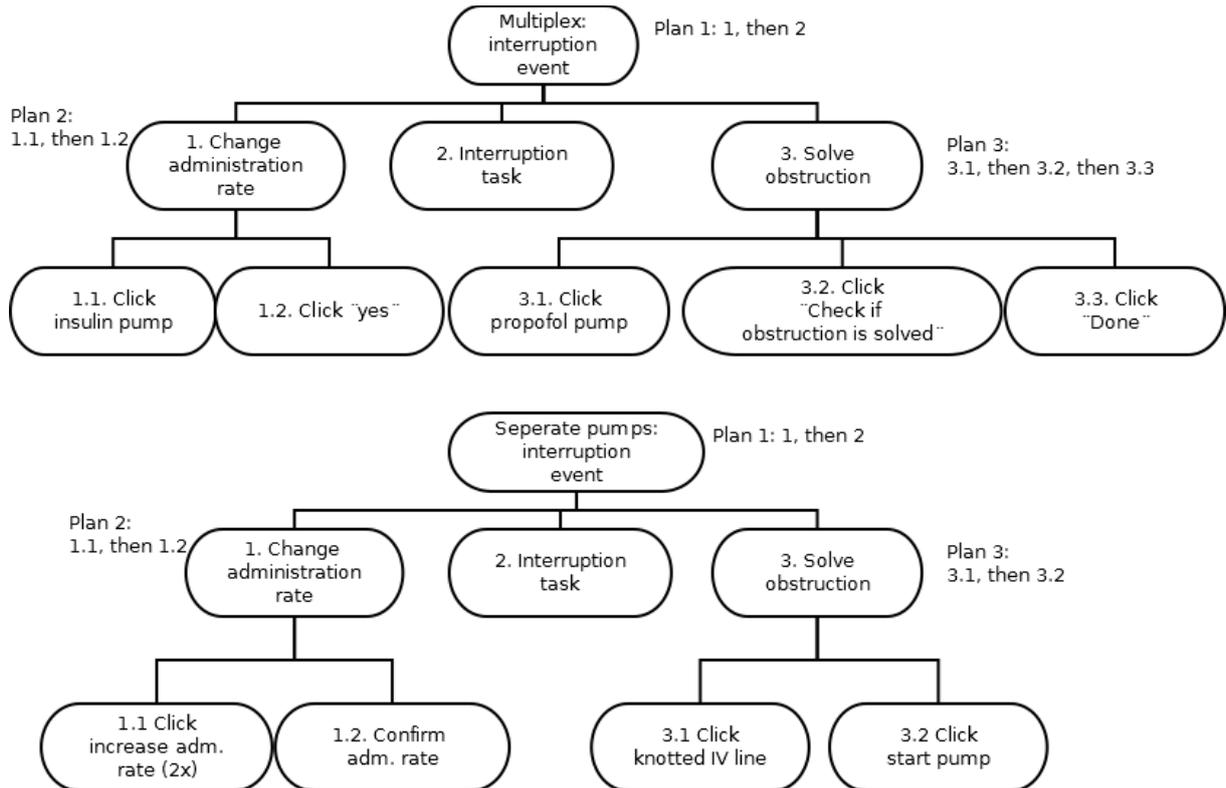


Figure 17: Hierarchical task analyses of the tasks related to the interruption event using the Multiplex user interface (top) and the seperate pumps interface (bottom).

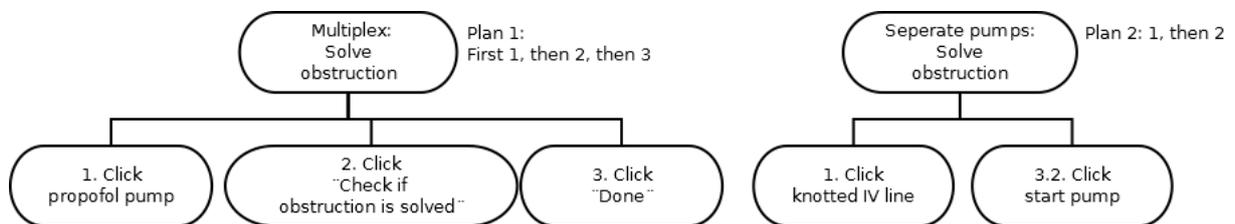


Figure 18: Hierarchical task analyses of the tasks related to the obstruction event using the Multiplex user interface (left) and the seperate pumps interface (right).

Questionnaire. The questionnaire consisted of 22 usability-related statements per user interface. The statements can be found under Appendix B. The statements were grouped in five categories:

- The *overall* category considered all statements.
- The *system appearance* category considered statements regarding the participant’s visual impression on the user interface.
- *Intuitive design* considered statements on whether or not it was clear how the user interface should be operated.
- *Ease of use* considered whether or not functionalities on the user interface were easy to use.
- *General impression* considered the overall impression and opinion about the user interface.

A rating using a seven-point Likert scale was used to measure the amount of agreement with each statement. The rating levels for the Likert scale were as follows: completely disagree, strongly disagree, disagree, neutral, agree, strongly agree and completely agree.

Design and procedure. Before commencing with the experiment, patients received an informed consent form that they were asked to read and sign. Participants received a description of a patient case on paper. Anonymous participant data, such as age, gender, ICU department, and years of working experience were gathered before commencing with the experiment.

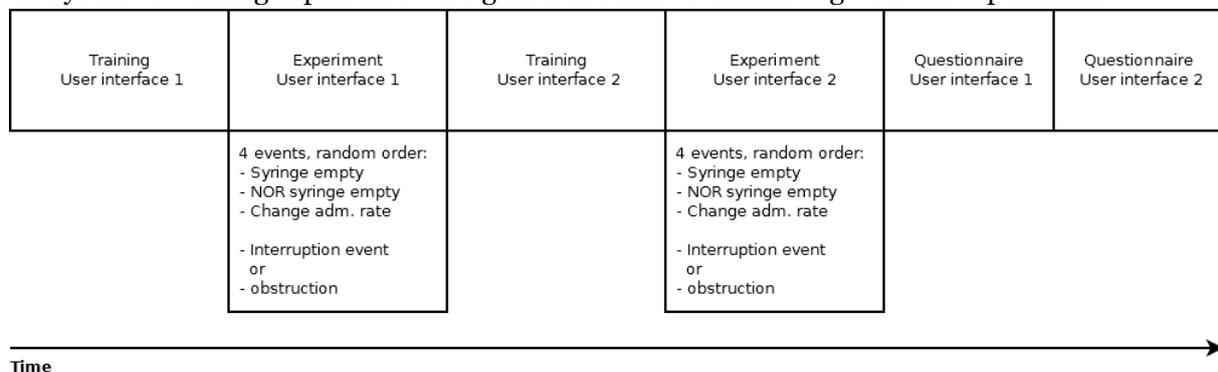


Figure 19: The structure of the experiment over time. If the interruption event occurred using one user interface, the obstruction event would occur using the other user interface.

The experiment consisted of two blocks of training and experimental tasks (Figure 19). Half of the participants started with the Multiplex user interface, the other half started with the separate pumps. During the training stage, the execution of all relevant tasks was explained and practiced. Participants were told that they would encounter several events which they had to deal with. How to deal with an event was practiced during the training stage. Participants were instructed to perform the tasks in the same way as they would with a real patient.

A clock in the top-right screen was used to indicate the simulated time of day. At the start of the experiment, the time was 8:30 AM and the simulated day ended at 4:00 PM. Events occurred at random moments in a randomized order during this day. After an event, participants could speed up time until the next event. The participant pressed the space bar in order to indicate that he or she was done dealing with the event, which would also speed up the time. If an alarm was still active, the time would not speed up, allowing the participant to finish the task. If a participant indicated that he or she was done with a task by pressing the space bar while the task was not finished, this was marked as an error.

During an event, time passed equally as fast as in real life (normal speed). As soon as an event started, a visual and audible alarm was presented on the pump where the alarm occurred or a dialog window (in the separate pump case) with a new order appeared.

With each user interface, 4 of 5 possible events occurred. If the interruption event occurred with the one interface, then the obstruction event would occur in the other. The occurrence of these events was balanced over all participants so that both events occurred equally often.

After finishing the experiment with the second user interface, a digital questionnaire was administered.

Data analysis. For the *syringe empty*, *NOR syringe empty* and the *change administration rate* events, a within-subjects design was used as these tasks occurred in both user interfaces. For the analysis of the *interruption* and *obstruction* event, a between-subjects design was used, as these tasks only occurred once per experimental session.

During the experiment, all clicks, response times, task execution times and errors were recorded. *The first response time* was defined as the time between the start of an event and the first action from the participant to start performing a task in order to deal with the event. For each event, there were four variables: the number of clicks during the event, the first response time, the total time of dealing with an event, and the number of errors.

A repeated measures analysis of variance was performed in order to compare the differences between the variables corresponding to the *syringe empty*, *NOR syringe empty* and the *change administration rate* events. An analysis of variance of the same variables, but for the *interruption* and *obstruction* event, was performed for the same goal.

Questionnaire responses were logged as numbers ranging from 1 to 7. These values represented the levels of the Likert scale as follows: 1 = completely disagree, 2 = strongly disagree, 3 = disagree, 4 = neutral, 5 = agree, 6 = strongly agree and 7 = completely agree. The difference in responses was analyzed using a two-tailed t-test.

7 Results

One of the main goals of this study was to create user interface with a better usability than the current IV system. Therefore, a user-based usability analysis was performed. In the following sections I will discuss the results of this analysis.

7.2 Empirical study

In the analysis of the *interruption* event, the data of 2 participants was could not be analyzed as, due to technical reasons, the obstruction failed to start. In the questionnaire, data from 4 participants was could not be analyzed due to a technical issue.

7.2.1 Number of clicks

In order to measure participants' performance during the execution of tasks, I looked at the number of clicks. A golden standard, which is the least number of clicks needed to perform the task correctly, was determined for each event using the HTAs in the previous chapter. For the *syringe empty* and *NOR syringe empty* events in the Multiplex condition, there were 2 golden standards: one using the checklist and one when the checklist was disabled by the user. The golden standards, together with the averages and standard deviations are displayed in Figure 20. A repeated measures analysis of variance was used to test for differences between both user interfaces in the *syringe empty*, *NOR syringe empty* and the *change administration rate* events. A between subjects analysis of variance was performed for the *interruption* and *obstruction* events.

In the *syringe empty* event, the number of clicks was higher in the Multiplex condition than in the separate pumps condition, this difference was significant, $F(1,15) = 43.636$, $p < 0.000$. In the *NOR syringe empty* event, the number of clicks was significantly higher in the separate pumps condition, $F(1,15) = 9.201$, $p < 0.05$. The same was the case in the *change administration* event $F(1,15) = 39.894$, $p = 0.000$. In the *interruption* event, there were more clicks in the Multiplex condition, $F(1,13) = 10.67$, $p < 0.05$. There was no significant difference between the two conditions in the *obstruction* event, $F(1,15) = 0.539$, $p = 0.475$.

In the Multiplex user interface, the possibility to close a dialog window using the standard x-button in the top-right corner was disabled, forcing the participant to make a choice during a dialog. Unfortunately, it is not possible to remove this button from the dialog window, as this is a default Java feature. As the participant clicked the x-button, a message appeared asking the participant to choose between two options, for example: accept an order or decline. There were two cases during the interruption event where this message was misread, leading to multiple attempts to close the dialog window and additional clicks.

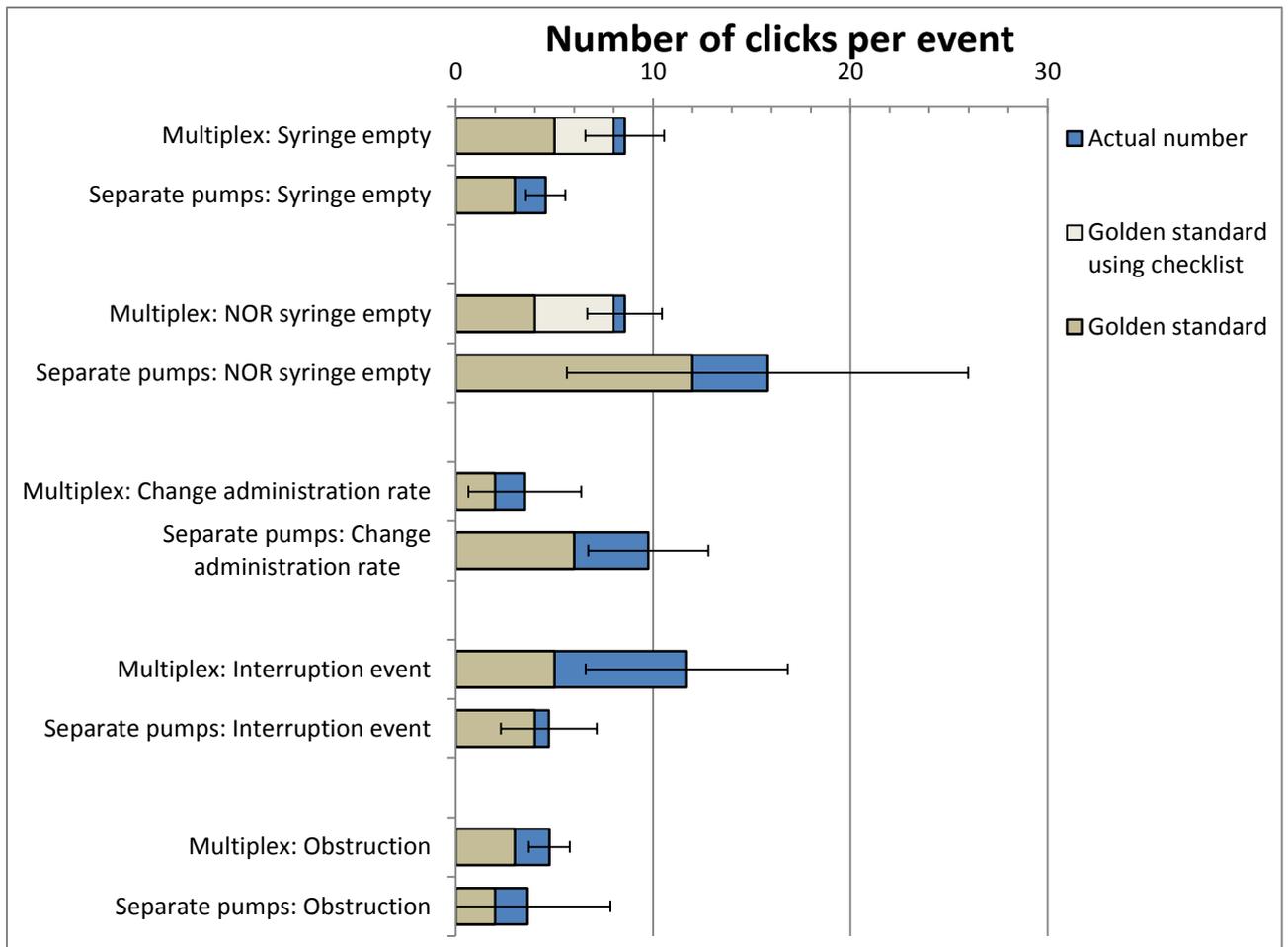


Figure 20: The actual number of clicks and golden standards per event. Error bars denote the standard deviations of the actual number of clicks.

7.2.2 First response times

In order to measure how quickly participants responded to the onset of an event, I looked at the first response times. The average first response times and the corresponding standard deviations are depicted in Figure 21. The first response times were significantly faster in the Multiplex condition in the *syringe empty*, *NOR syringe empty*, *change administration rate* and the *interruption event*. The results of statistical tests for these 4 events were as follows: *Syringe empty*, $F(1,15) = 8.595$, $p < 0.05$. For the *NOR syringe empty* event, $F(1,15) = 4.904$, $p < 0.05$. For the *change administration rate* event, $F(1,15) = 7.642$, $p < 0.05$. And for the *interruption event*, $F(1,13) = 9.799$, $p < 0.05$. There was no significant difference in first response times for the *obstruction event*, $F(1,15) = 0.019$, $p = 0.893$.

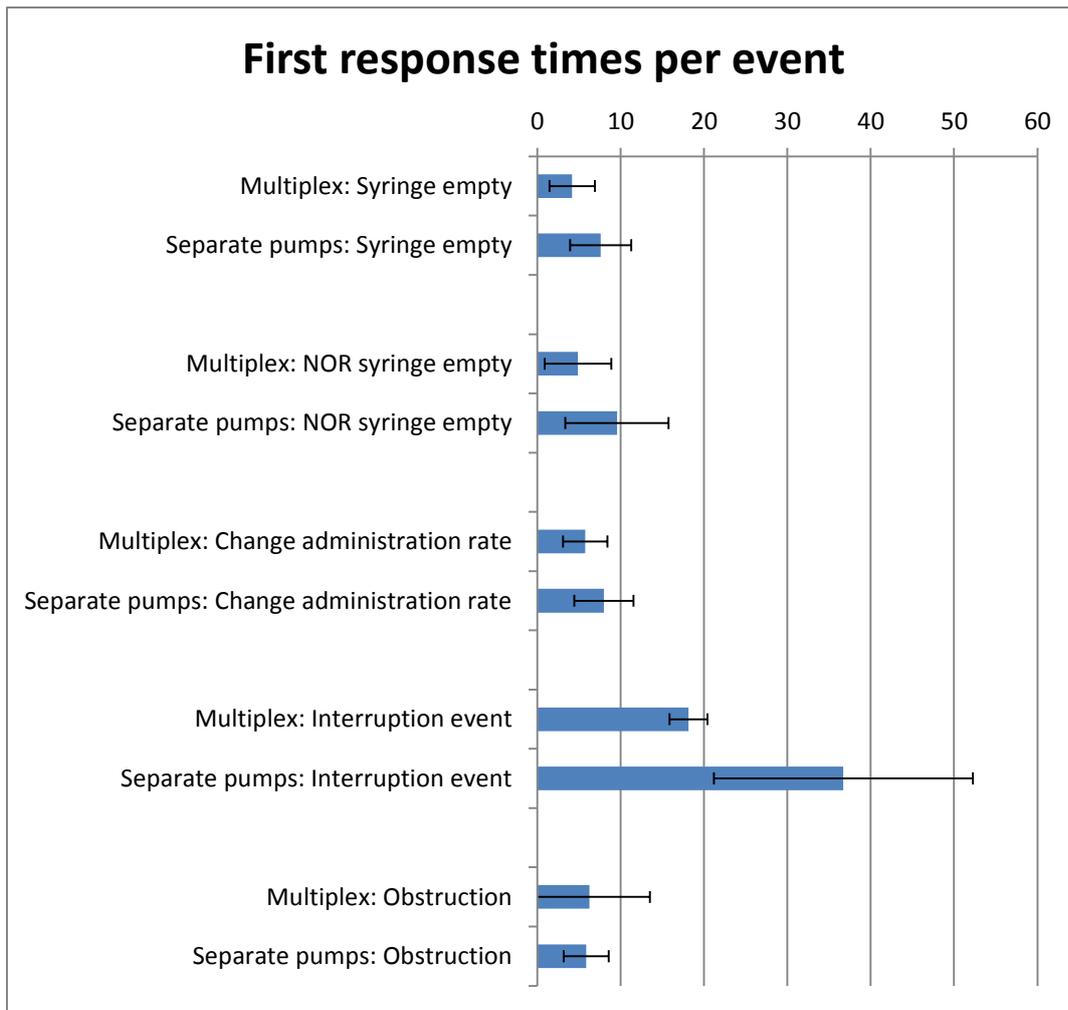


Figure 21: Mean values of first response times per event. Error bars represent standard deviations.

7.2.3 Total execution times per event

In order to measure participants' performance during the execution of tasks, I looked at the total execution times per event. The total execution times per event are displayed in Figure 22. There was no significant difference in execution times between the conditions in any event. The results of statistical tests for the 5 events were as follows: For the *syringe empty* event, $F(1,15) = 2.925$, $p = 0.108$. *NOR syringe empty*, $F(1,15) = 1.635$, $p = 0.221$. *Change administration rate*, $F(1,15) = 0.50$, $p = 0.826$. *Interruption event*, $F(1,13) = 2.37$, $p = 0.149$. And the *obstruction* event, $F(1,15) = 0.257$, $p = 0.620$.

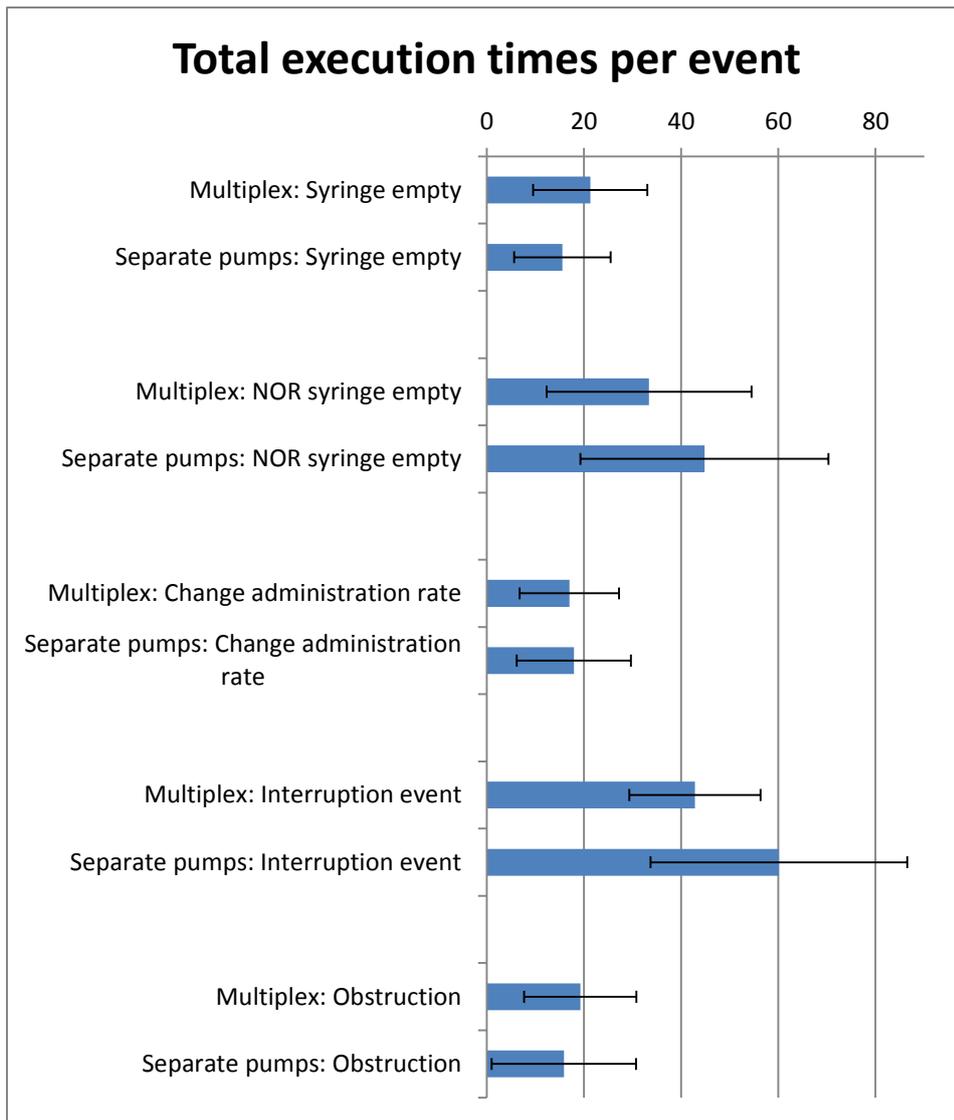


Figure 22: The average total time for completing the tasks corresponding to each event. Error bars denote the standard deviations.

7.2.4 Errors

Errors during the performance of tasks were identified for the Multiplex and separate pump conditions. Table 6 lists all errors during the entire experiment.

An *ignored alarm* was defined as an event where it took more than 1 reminding alarm (after a 10 second delay after the initial alarm) in order for the participant to start performing the relevant actions. Ignored alarms were eventually dealt with by the participant, as the experimental setup did not allow moving on to the next event if an alarm was still active.

Table 6: The occurrence of errors and their description using separate pumps.

Event	Condition	Description of the error
Syringe empty	Separate pumps	Participant ignored empty syringe alarm
NOR syringe empty	Multiplex	Participant stops the noradrenalin pump. Then proceeds to the checklist, after which the system automatically corrects the error by starting the pump
Interruption	Separate pumps	Participant did not adjust the administration rate of the morphine pump
		Participant ignored obstruction alarm
		Participant ignored obstruction alarm and forgot to adjust the administration rate of the morphine pump (<i>2 errors</i>)
	Multiplex	Participant pressed the space bar (indicating that the task was finished), while the administration rate of the insulin pump had to be adjusted first
		Participant clicked on the Potassium Chloride pump instead of the propofol pump. Participant notices the error and recovers from it.
Obstruction	Separate pumps	The task was to resolve an obstruction in the Nimotop pump. Participant starts with replacing the Nimtop syringe. Then, the administration rate of noradrenaline is adjusted from 8 to 10 ml/h. (<i>2 errors</i>)

8 errors occurred in total in the separate pump condition and three in the Multiplex condition. A paired t-test was performed to see if there was a significant difference in the number of errors per condition. There was a significant difference in the number of errors between the separate pump condition ($M=0.50$, $SD=0.730$) and with the Multiplex Infusion System ($M=0.06$, $SD=0.250$); $t(15) = 2.150$, $p < 0.05$.

7.2.5 Questionnaire responses

Figure 23 displays boxplots of grouped ratings for the statements in de questionnaire. Boxplots of ratings per statement can be found under Appendix B. The statements were grouped as follows:

- Overall average: all 22 statements
- System appearance: statement 2, 3, 4 and 5
- Intuitive design: statements 6, 7, 8, 9, 11, 19
- Ease of use: statements 10, 15, 16, 17, 18
- General impression: statements 1, 12, 14, 20, 21, 22

Group differences were found in ratings for *system appearance* and *intuitive design*. For *system appearance* there was a significant difference between the Multiplex condition ($M = 6.28$, $SD = 0.84$) and the separate pumps condition ($M = 5.85$, $SD = 1.33$), $t(59) = 2.001$, $p < 0.05$. There was also a significant difference in rating for *intuitive design* between the Multiplex condition ($M = 6.0$, $SD = 0.88$) and the separate pumps condition ($M = 5.65$, $SD = 1.16$), $t(71) = 1.99$, $p < 0.05$.

Significant differences were found in ratings on two individual statements. *This system looks nice* was rated significantly higher for the Multiplex user interface ($M = 5.92$, $SD = 0.996$) than for the

separate pumps ($M = 4.83$, $SD = 1.467$), $t(11) = 2.315$, $p < 0.05$. The statement *I enjoy working with this system* was rated significantly higher for the separate pumps ($M = 5.58$, $SD = 1.165$), $t(11) = 2.262$, $p < 0.05$. Responses to all other questions were not found to be significantly different between conditions.

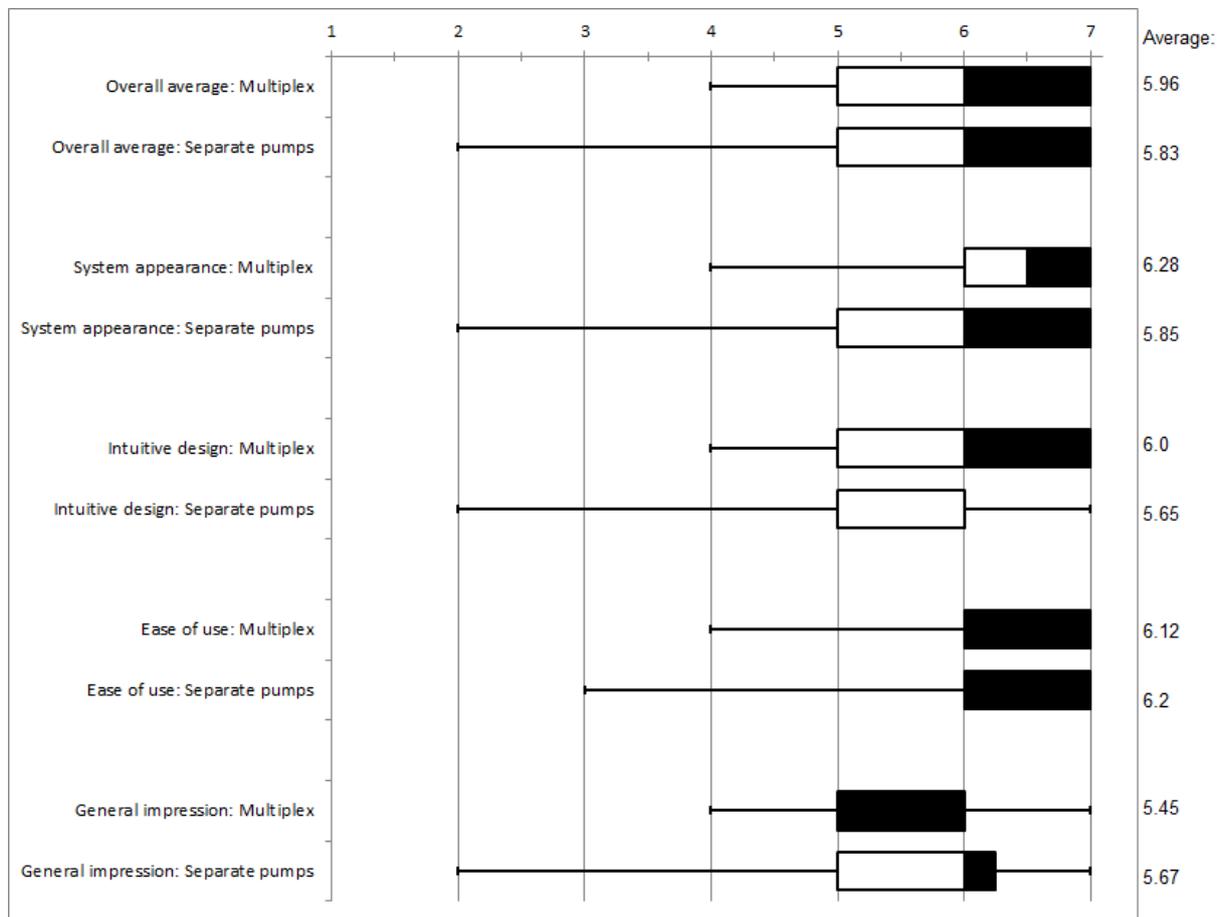


Figure 23: Boxplots of grouped questionnaire responses. Group averages are displayed on the right of this figure. Error bars denote standard deviations. There was a significant difference in *system appearance* and in *intuitive design* between the Multiplex and Separate pumps user interface.

7.2.6 Other results

In the separate pump condition, there were three different ways to perform the tasks corresponding to event 2 (Noradrenalin empty). For this task, there was a second pump available which could be used. One participant changed the administration rate from 8 ml/h to 4 ml/h on the almost empty pump. The additional pump was also set up at 4 ml/h, after which the participant increased the administration rate stepwise on the new pump and decreased the administration rate of the first until the first pump stopped and the new pump was set at 8 ml/h. Another participant set the administration rate of the new pump to 8 ml/h, started the pump and immediately stopped the pump with the almost empty syringe. Four participants did not use the additional available pump. These participants stopped the pump, replaced the almost empty syringe and started the pump again. The other ten participants gradually decreased the administration rate of the first pump and increased the administration rate of the second pump, maintaining the total administration rate at 8 ml/h.

8 Discussion

In this chapter, I will start with discussing the results of the feasibility analysis on IV tubing in section 8.1 and of the empirical study in section 8.2. I will then discuss the limitations and strengths of this study in section 8.3. Ideas for future research will be discussed in section 8.4.

8.1 Feasibility analysis

One of the main goals of this study was to decrease the number of lumens that were necessary for IV therapy. The analysis of IV tubing in chapter 5 indicated that with the Multiplex infusion system, less lumens would be necessary than with the current IV therapy methods. As most patients in the ICU have a triple-lumen catheter, the results suggest that in most cases, a double lumen catheter would be enough. Half of the patients in the analysis had a (peripheral) catheter additional to the standard triple-lumen catheter, which would not be required using the Multiplex infusion system. This could prevent physical discomfort, reduce infection risk in a large group of patients, save time and reduce costs. It is important to note that this analysis featured a relatively small number of IV tubings. As approximately 3000 patients are admitted in the ICU each year, there are many different types of patients that could not be included in this feasibility analysis. Therefore, extending this analysis to a larger group of patients may yield in different results.

8.2 Empirical Study

In this section, I will discuss the results of the empirical study. I divided the discussion into four topics: The number of clicks, total execution times, first response times, errors and questionnaire responses.

8.2.1 Number of clicks

In this study, an important goal was to create a user interface with a better usability and a lower error rate than the current system where the nurse controls multiple pumps separately. The Multiplex user interface was designed to assist the nurse in difficult tasks and to take over stages of the IV process which are prone to error.

Based on HTAs of the experimental tasks with both user interfaces, golden standard were obtained. Results showed that when the golden standard was higher for one user interface, then the actual number of clicks was also higher with that user interface. The average number of clicks was consistently higher than the golden standard, which was to be expected. However, in some cases the number of clicks was up to twice as high as the golden standard. In the Multiplex condition, this may be explained by inexperience with the system resulting in additional clicks. In the Multiplex condition, the possibility to close a dialog window using the standard x-button in the top-right corner was disabled. As the participant clicked the x-button, a message appeared asking the participant to choose between two options, for example: accept an order or decline. As this was sometimes misread, this led to multiple attempts (and clicks) to close the dialog window which affected the number of clicks.

In the separate pumps condition, the participants worked with a simulation of the infusion pumps they operate on a daily basis. As the results showed, there are multiple strategies to perform the same task in the separate pump condition, this has affected the average number of clicks and the variance between the participants.

Although differences in the number of clicks were found in some events, neither user interface had an overall lower number of clicks. The Multiplex user interface generally required more clicks than the separate pumps interface when a checklist was used. As this checklist may reduce errors during the execution of physical tasks (attaching IV lines, opening valves), the additional clicks are considered to be acceptable.

8.2.2 First response times

The first response times were generally quite high. The fastest average response time was 4 seconds in the Multiplex condition during the *syringe empty* event. This may be explained by the amount of visual search that was required to find the pump corresponding to the event, followed by the time it took to read and interpret the relevant task before starting the execution of the task. During the *interruption* event, the first response times were roughly between 40 and 60 seconds. This can be explained by the fact that the participant was required to read the task instructions and had to look up how long it took before a certain syringe was empty before the first click could take place. Therefore, the first response time is a valid measure to use in this experiment.

In the (*NOR*) *syringe empty*, *change administration rate* and *interruption* event, participants responded significantly faster to the onset of an event in the Multiplex condition than in the condition with separate pumps. Only in the *obstruction* event there was no difference in first response times. The difference in the first four events could indicate that it is easier to discriminate between pumps using the Multiplex infusion system, allowing participants to start performing tasks relevant to the event sooner. On the Multiplex interface, the panel representing the pump entirely changes color to red or green, which may be more salient than the alarm light in the top-right corner of the simulated infusion pumps. In the real ICU, this could make an important difference in emergency situations when a quick and accurate response to an alarm is required.

8.2.3 Event execution times

The results showed that there was no difference between the two conditions in the time that it took to perform the tasks related to the five experimental events. This indicates that tasks with neither of the two user interfaces are more time consuming than with the other user interface. The lack of a difference in execution times indicates that novice users of the Multiplex user interface are equally as fast as expert users of the current infusion system.

8.2.4 Errors

One of the goals of this study was to reduce the likelihood of errors in IV therapy. Results showed that significantly less errors occurred using the Multiplex user interface. Errors were generally less severe and in two out of the three errors with this interface, the error did not have any consequences as the participant noticed the error or the system made sure the error was handled correctly. In one of these three cases, the participant tried advancing to the next event before the current task was finished. The experimental model forced the participant to finish the task before the next event could start. In a real situation, it is possible that the nurse would have walked away at that point. Although the alarm would keep repeating, which increases the likelihood that another nurse will notice the alarm, it is preferable that the alarm is dealt with immediately.

In the separate pumps case, alarms were ignored four times and an order to change an administration rate was neglected twice. Five out of eight errors with this system occurred during the *interruption* event. The interruption event consisted of 3 tasks: an order to change an administration rate, an assignment to look up information on a pump and an obstruction. According to the goal-activation model (Altmann & Trafton, 2002), the nurse would need to maintain a representation of three goals corresponding to these tasks during the interruption event. The first two tasks in this event followed each other up rapidly and the third was introduced during the execution of the second task. This increased the cognitive workload, which increases vulnerability to errors. This also could have affected the rehearsal time, making it less likely that a goal-node is retrieved successfully (Salvucci & Taatgen, 2008). As working memory should be able to hold between 5 and 9 chunks of information (Miller, 1956), the three goal-representations are unlikely to use up all working memory capacity. It is possible that participants were also maintaining other goals which were not directly related to the experiment. As most participants returned to work in the ICU after the experiment, they may have been maintaining

other goals that were related their work or personal situation. Therefore, it is likely that the working memory capacity of some participants was fully used during the interruption task, which resulted in errors. The models of goal-activation and threaded cognition could explain how the interrupting task causes these errors during the interruption event.

8.2.5 Questionnaire

The grouped questionnaire results showed that the Multiplex infusion system had significantly higher ratings for *system appearance* and *intuitive design*. Results on other categories showed that there was no overall subjective preference, nor a difference in ease of use or general impression.

Analysis of the individual statements indicated that participants liked the appearance of the Multiplex user interface more than that of the separate pumps. However, they enjoyed working with the separate pumps more. When asked after the experiment, several participants indicated that, due to the many years of working with the current infusion pumps, they knew the system very well and therefore enjoyed working with the system. Their answers on the questionnaire were influenced by their previous experience with the system. Multiple participants mentioned that they required more experience with the Multiplex Infusion System in a real work environment in order to rate its usability properly.

Based on the analysis of the individual statements it is not possible to conclude which system had the highest subjective preference. However, the grouped questionnaire results indicate a higher preference for the Multiplex user interface.

8.2.6 Interpretation of results

Nielsen (1994a) suggested that a system with good usability met the following criteria: *learnability, efficiency, memorability, low error rate and satisfaction*. I discussed these criteria in chapter 4. I will now summarize the results of the user-based usability analysis and link these results to Nielsen's criteria for usability. As participants encountered each user interface only once, memorability could not be tested in the experiment.

Although there were differences in numbers of clicks during multiple events, there were no differences in the total time that was needed for dealing with an event. This result indicates that the additional steps due to the use of a checklist in the Multiplex user interface did not influence the speed in which tasks were performed. Based on the recorded number of clicks and time to deal with an event, a difference in efficiency could not be found.

First responses were generally faster with the Multiplex user interface. This may indicate that it is easier to discriminate between infusion pumps on this user interface than in the conventional setup. The fact that participants could start dealing with an event earlier with Multiplex user interface, indicates a higher *efficiency*.

Participants were experts in the separate pumps condition, but were novices when it came to using the Multiplex user interface. Despite this fact, participants made *fewer errors* with the Multiplex user interface and were equally as fast as with the familiar user interface. This indicates that working with the Multiplex user interface is easy to learn.

Based on the analysis of individual statements in the questionnaire it cannot be said which user interface was more *satisfying* for the user. However, results from the grouped questionnaire indicate a higher preference for the Multiplex user interface based on *system appearance* and *intuitive design* aspects.

The Multiplex user interface demonstrated a higher efficiency and a lower error rate than the separate pumps user interface. The Multiplex user interface was also easy to learn, but its learnability cannot be compared to that of the separate pumps user interface as participants were already familiar with the separate pumps condition. Users of the Multiplex user interface were generally more satisfied with its appearance and intuitive design aspects. Overall, the Multiplex user interface has a better usability than the separate pumps user interface.

8.3 Limitations and strengths of this study

The feasibility analysis featured only a small number of IV tubings. Although the results were statistically significant, the type of patients in an ICU may vary from day to day, which may not be representative for the total population of ICU patients. I suggest that this analysis is repeated using a larger sample size and during a longer period of time in order to be able to generalize the outcome to a larger population of ICU patients .

The empirical study featured a simplification of the tasks of an ICU nurse. Some aspects of this study may not be generalizable to a real environment as the tasks in the experiment do not feature all aspects of their real-world counterparts. For example, attaching a new syringe in the experiment was a matter of a single click, while the real-world task involves several subtasks. The real world task involves more complexity, while the experimental task featured a simplification of the ICU nurse's tasks related to IV therapy. On the other hand, the fact that errors already occurred using a simplified version of real-world tasks, could mean that errors are even more likely in the real world task.

The audible alarms of a real infusion pump sound from a speaker inside the pump, which could make localizing the alarming pump easier. However, this factor was not included in the experiment as all alarms sounded from the same source. This may have affected the first response times.

A factor that could have influenced the performance in this experiment and may have influenced the results of the questionnaire, is that most participants have years of experience with the current infusion system. Even an ICU nurse with only one month of experience would have been likely to have operated an infusion pump over a hundred times. Despite the influence of previous experience, participants made less errors using a completely new system. Participants also completed tasks equally as fast with the Multiplex user interface as with a simulation of the currently used IV pumps. This indicates that working with the Multiplex user interface is easy to learn and this system is more effective in preventing errors. Having more experience with the Multiplex user interface may emphasize the difference between both user interfaces even more.

Previous studies focused on evaluating the usability of individual infusion pumps and suggesting changes to their design. This study is unique in the sense that it presents an entirely new user interface for the control of *multiple* infusion pumps and it compares the usability of this user interface to that of the conventional operation of multiple infusion pumps, using a user-based usability evaluation. A strength of this study is that it demonstrated how a user-friendly user interface can prevent errors in the operation of multiple infusion pumps.

Previous observational studies in ICUs were not able to demonstrate the influence of interruptions on the occurrence of errors. Interruptions are difficult to predict and it is difficult to assess whether or not an interruption is the cause of an error. This study included a task with a controlled interruption. A total of 11 errors was recorded of which 7 occurred during the interruption task. The goal-activation model (Altmann & Trafton, 2002) and the model of threaded cognition (Salvucci & Taatgen, 2008) were used to explain how an interruption could cause the decay of a goal in working memory. The fact that these errors occurred while performing simplified tasks in a controlled and simulated environment, suggests that errors may be more frequent and severe in a real ICU.

8.4 Suggestions for further research

Based on the results of the current study, I have the following suggestions for future research.

The results of the empirical study showed that nurses use different strategies for completing the same task. It would be interesting to perform a hierarchical task analysis on the execution of several IV therapy related tasks as they are being performed by multiple different ICU nurses. This may help to identify how often certain strategies are used by ICU nurses. Some strategies may involve more manual actions than others, which may be inefficient or could have a

higher risk of error. The results of this analysis could be used to train nurses to become more efficient and may reduce errors.

The tasks during the interruption event could be modeled using the threaded cognition model (Salvucci & Taatgen, 2008). In section 8.2.4 I suggested that the errors caused by the interruption in this event could be explained by this model. The model could also be used to predict errors during interruptions. Predictions by the model could be compared to data from an experiment which features a simulation involving multiple ICU nurses. The UMCG has an advanced simulation center which is used for training of medical staff using realistic simulations. An experiment in the simulation center, which allows for a realistic and controllable simulation of an ICU, could test the effects of different interruptions and cognitive workload on the performance of IV therapy related tasks. This experimental setup would also eliminate the need for simplifications of tasks, such as replacing an empty syringe and solving an obstruction in an IV line, allowing for a better generalizability to real tasks in the ICU.

9 Future work

In this thesis, the first steps were taken in the development of the Multiplex infusion system. In order to finalize this project, there are several theoretical and engineering challenges that need to be faced and goals that need to be achieved:

Gain control over all infusion pumps for a single patient from a control system proximal to the patient. This includes controlling both the syringe pumps and volumetric pumps.

Create an interactive system that guides the user in how to connect the tubing for a patient. This will be a subsystem of the Multiplex Infusion System.

The compatibility matrix (Appendix E) is incomplete and knowledge about currently unknown interactions between medication should be added. Ideally, the Multiplex Infusion System knows all compatibilities of all combinations of medication in the ICU. However, it may be a costly operation to test all interactions. Therefore, I suggest to perform an empirical study in order to obtain frequency distributions of combinations of medication in the ICU. The most frequently used combinations should be tested and knowledge about their compatibility could then be implemented in the system.

Test the mixture of multiple substances in a single IV line in order to find the required amount of buffer fluid. This is required to alternate between medication through a single lumen safely.

The Multiplex Infusion System should be to be connected to the upcoming patient data management system (PDMS), so that these systems can exchange information.

The Multiplex Infusion System should be able to overrule all features of the current infusion pumps, like alarms, display messages and administration rates. In order to be able to fully control these pumps, collaboration with infusion pump manufacturers is required.

As it is important to know how accurate syringe pumps and volumetric are at high and low administration rates, the intrinsic variation of the infusion pumps needs to be tested.

Contact the Dutch Health Inspection (Dutch: Inspectie voor Volksgezondheid) to assess whether or not the Multiplex Infusion System complies with current healthcare regulations.

10 Conclusions

In this thesis, I illustrated that there are many problems with the current IV therapy system. The Multiplex infusion system was proposed to reduce and solve current problems with usability, patient safety and comfort. A feasibility study indicated that this system could be able to reduce the number of required lumens and therefore could reduce infection risks and discomfort.

In this study, I have shown how the usability of infusion pumps can affect the occurrence of errors related to intravenous therapy. A user-friendly user interface for the Multiplex infusion system was developed and its usability was compared to that of the current method of operating multiple infusion pumps in a user-based usability analysis. Results suggest that the Multiplex infusion system has an overall better usability and could reduce the number of errors by partially automating tasks and supporting the ICU nurse during the error prone stages of IV therapy.

In this thesis, I used theoretical models to explain how interruptions can cause the decay of goals corresponding to tasks, which can lead to errors. Experimental results indicated that errors occurred more during an event that featured such an interruption. Results of this study indicate the implementation of the proposed Multiplex infusion system could benefit the safety of patients in an ICU.

Acknowledgements

I would like to thank my external supervisor Maarten Nijsten for his support, ideas and enthusiasm during the course of this project.

I would also like to thank my internal supervisor Fokie Cnossen for thinking along since the start of the project and providing useful feedback and ideas during every stage of the project.

My thanks go out to Wim Dieperink for providing accommodation in the UMCG and making sure I had everything I needed for this project.

Thanks to Koos van Ringelsteijn for bringing me into contact with everyone within the UMCG who contributed to this project.

I am grateful to Johan de Jong for believing in this project and allowing me to continue the project within the UMCG.

I would like to thank Ellen Swiers and Marisa Onrust for showing me around in the ICU and answering all my questions.

Finally, I would like to thank my family and friends for their support during this project.

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Appendix A: Definitions

Algorithm: A set of computational rules for solving a problem in a finite number of steps.

CIV catheter : IV catheter that is placed in a central vein, and thus allows the administration of concentrated or otherwise potentially damaging fluids if given via a peripheral vein.

Connector: Any Luer-lock connectable object that is used to connect the syringe of an infusion pump to an IV catheter. This includes infusion lines, stopcocks, syringes and catheters.

Double-lumen catheter: A catheter containing two lumens, therefore allowing for two separated flows of infusion fluids.

Infusion packet: Small amount of a single infusion fluid, the minimal and central element of the Multiplex infusion concept.

Infusion tree: One or more infusion pumps connected to a single lumen that is directly placed with its tip in a vein of a patient through a funneling arrangement of one-on-one connecting tubings and valves.

IV catheter: catheter that is placed in a vein of the patient. Contains one or more lumens.

IV configuration: The way that all IV lines are (inter)connected for a single patient. Also referred to as *tubing*.

IV treatment (NL: intraveneuze behandeling): Intravenous treatment or intravenous therapy is the infusion of fluids into the vein of a patient.

Lumen: A hollow tube that allows for the insertion of a fluid into the bloodstream of a patient.

Luer-lock: Standardized system of fluid fittings which are used to make leak-free connections between the male and female part of medical equipment.

Multiplex infusion system: An automated control system that controls multiple infusion pumps simultaneously in order for multiple different fluids to be administered sequentially through a single lumen.

Peripheral catheter: IV Catheter that is placed in a peripheral vein, which allows the administration of fluids into the bloodstream of a patient.

Peripheral vein: Any vein that is not inside the chest or abdomen.

Pump profile: (alternatively: administration profile) Settings for administering infusion fluids in a specific manner. (E.g. continues infusion, gradual increase or

decrease in flow rate).

Single-lumen catheter: A catheter containing one lumen.

Syringe (NL: spuit): A syringe consists of a plunger that fits into a cylindrical tube. The plunger can be pushed or pulled inside the tube, which allows for the syringe to expel or take in fluids through the open end of the tube. Often, the open end is fitted with a male luer-lock tip.

Syringe pump (NL: spuiten-pomp): A mechanical device used for the administration of a predetermined volume of infusion fluid to a patient by gradually pushing the plunger of a syringe.

Triple-lumen catheter: A catheter containing three lumens, therefore allowing for three separated flows of infusion fluids.

Tubing: The configuration of connectors that connect from any infusion pump to any catheter in a patient receiving IV treatment.

Usability: The user-friendliness or ease of use of a device.

User-interface (NL: gebruikersinterface): The system by which a person (the user) interacts with a machine. It allows the user to send input to the machine and receive feedback from it.

Volumetric pump (volumetrische pomp): infusion pump designed to deliver moderate to large flows (i.e. 5 to 999 ml/hour).

Appendix B: Usability Questionnaire

Below you will find the statements from the questionnaire. All statements were rated for the Multiplex Infusion System and the current setup of infusion pumps. Statements were provided in Dutch and a translation into English is provided below. A rating was given using a 7-point Likert Scale. Figure 24, 25 and 26 display boxplots of the responses to the statements in the questionnaire.

Number	Question in Dutch	Question in English
1	Dit systeem is gemakkelijk te gebruiken	This system is easy to use
2	Dit systeem is nodeeloos complex	This system is unnecessarily complex
3	Dit systeem ziet er mooi uit	This system looks nice
4	Het hoofdscherm is overzichtelijk	The main screen is clear and orderly
5	Er wordt efficiënt gebruik gemaakt van de ruimte op het scherm	The space on the screen is used efficiently
6	De informatie op het scherm maakt goed duidelijk wat het systeem aan het doen is	The information on screen makes it clear what the system is doing
7	Het is duidelijk welke functie elke knop heeft	It is clear which function belongs to a button
8	Het is makkelijk om de verschillende infuuspompen van elkaar te onderscheiden	It is easy to discriminate between infusion pumps
9	Dit systeem geeft duidelijke feedback op mijn handelingen	The system delivers clear feedback on my actions
10	Fouten zijn eenvoudig te herstellen met dit systeem	Mistakes are easy to correct on this system
11	Funcies die ik nodig heb, kan ik makkelijk vinden	I can easily find the functions I need
12	Ik heb het gevoel dat ik controle heb over het systeem	I feel like I am in control of this system
13	Ik kan efficiënt werken met dit systeem	I can work efficiently with this system
14	Ik denk dat dit systeem veilig is	I think this is a safe system
15	Ik kan gemakkelijk een dosering aan te passen	I can easily adjust the administration rate
16	Ik kan gemakkelijk een spuit verwisselen	I can easily replace a syringe with this system
17	Ik kan goed zien hoe vol een spuit nog is	I can easily see how full a syringe is
18	Ik kan makkelijk zien hoe lang het duurt tot een spuit leeg is	I can easily see how long it takes until a syringe is empty

19	Als er een alarm afgaat, is het mij duidelijk wat er aan de hand is	It is clear to me what I should do in case of an alarm
20	Ik werk graag met dit systeem	I enjoy working with this system
21	Ik zou (de directie van) het UMCG aanraden om met dit systeem te gaan werken	I would recommend the (CEO of the) UMCG to work with this system
22	Ik vond de opdrachten met dit systeem makkelijk om uit te voeren	The tasks with this system were easy to perform

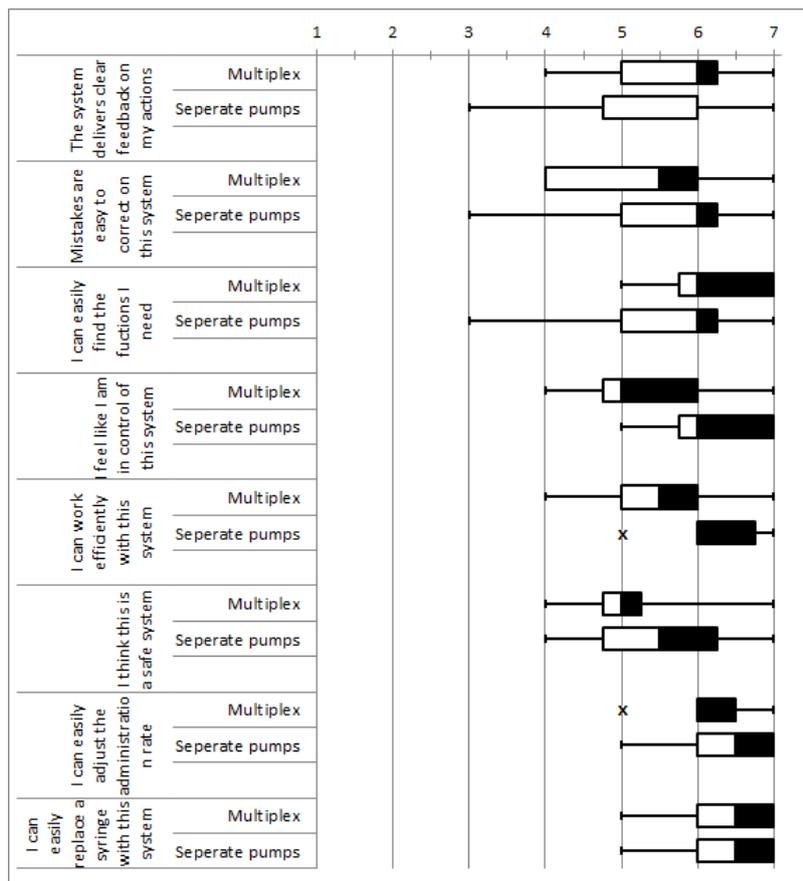


Figure 24: Boxplots of responses to the first 8 statements. Error bars indicate standard deviations.

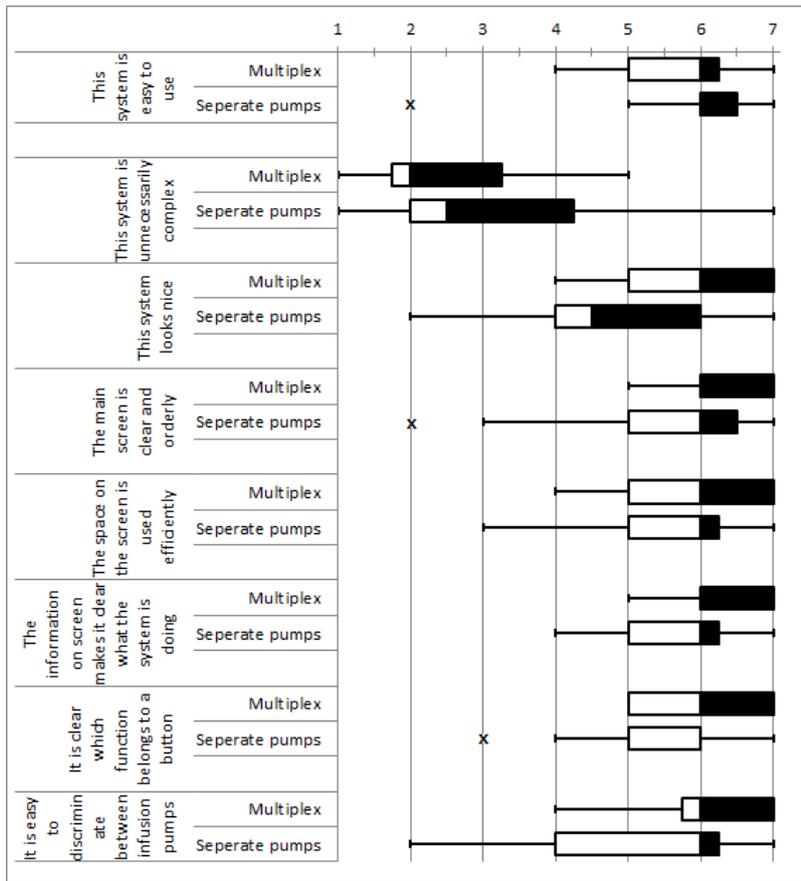


Figure 25: Boxplots of responses to statements 9-16. Error bars indicate standard deviations.

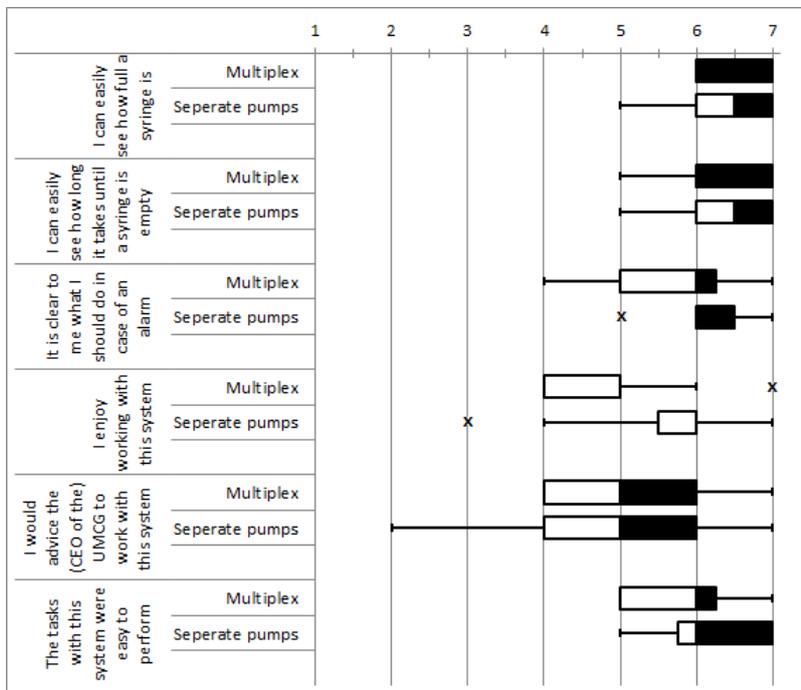


Figure 26: Boxplots of responses to statements 17-22. Error bars indicate standard deviations.

Appendix C: Hierarchical Task Analyses

The following tree diagrams depict parts of the IV therapy process. The colors in the HTA trees indicate who executes that part of the process. Figure 27 features a legend for the HTA trees.

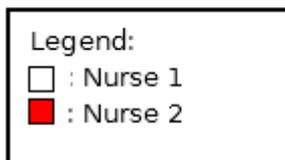
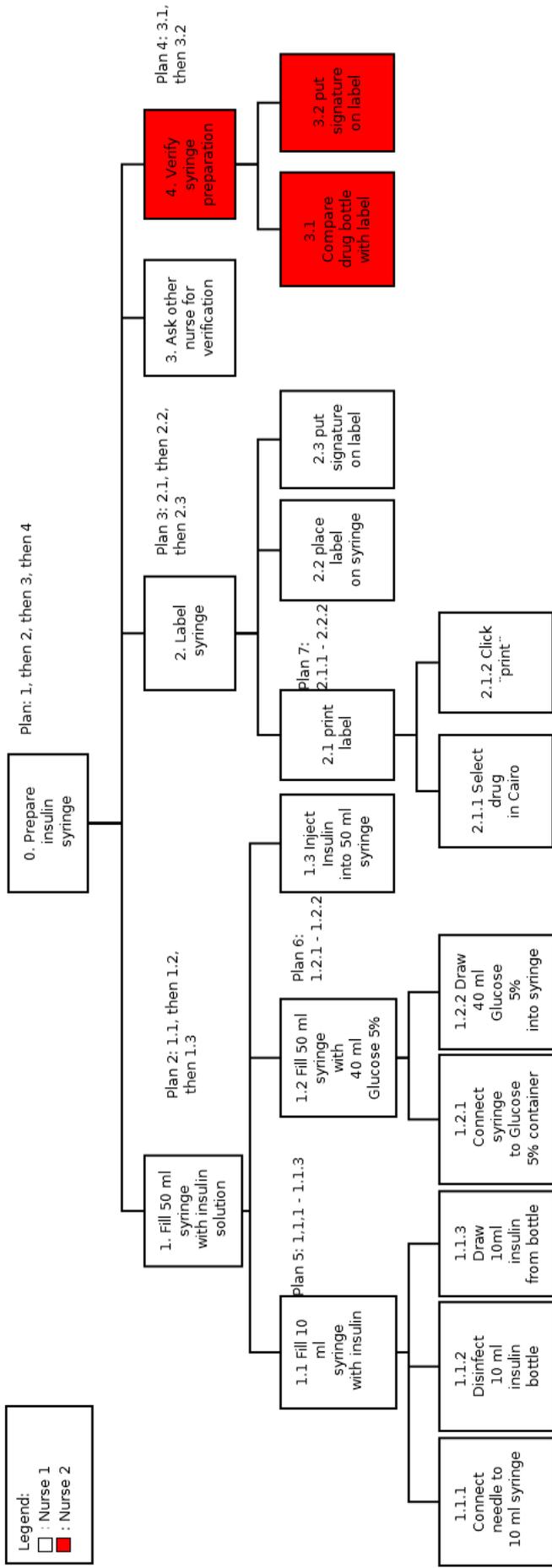
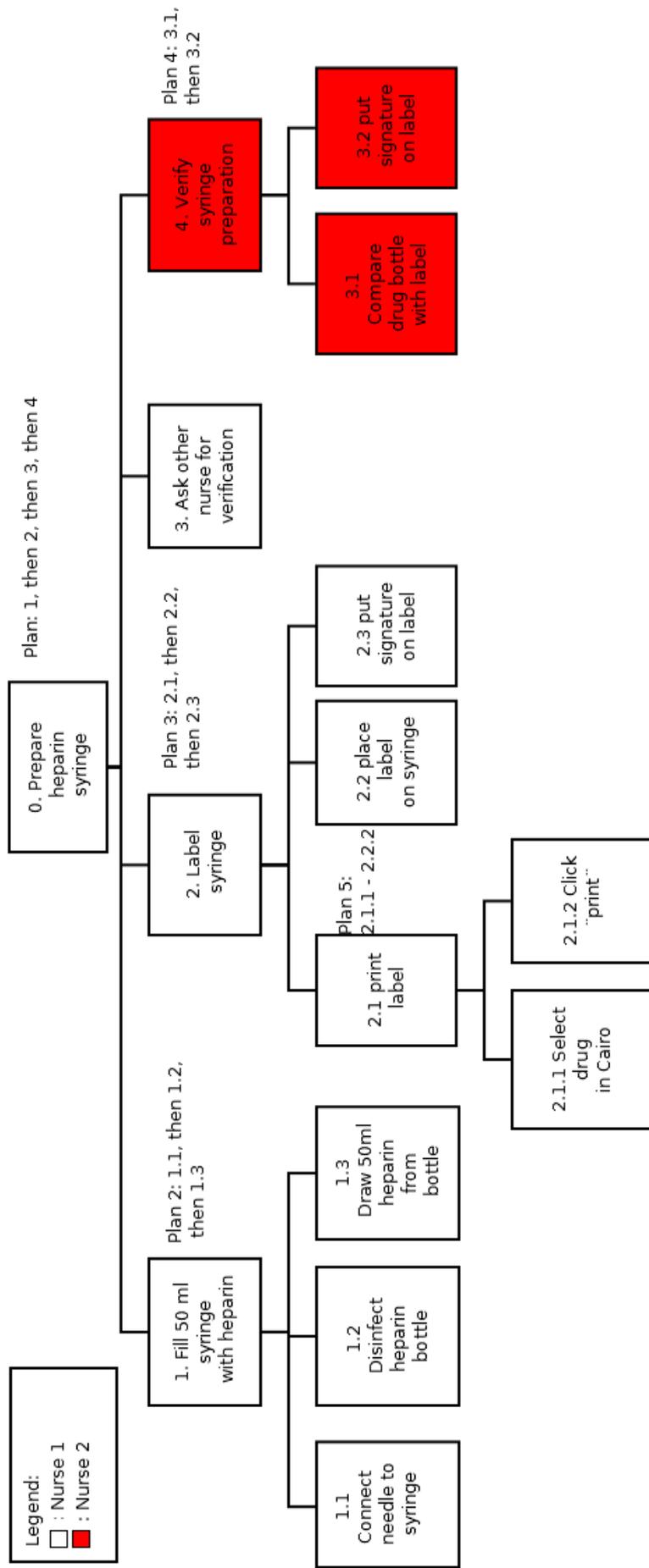


Figure 27: Color clarification for HTA trees





Appendix D: Feasibility Analysis

Below you will find the results of the feasibility analysis. Figure 28 displays the legend corresponding to the IV tubing analyses. Table 7 lists the abbreviations used in the analysis. Figure 29 displays the template that was used for drawing out the IV Tubings. The following tubings are digitalized versions of the IV tubings that were drawn out.

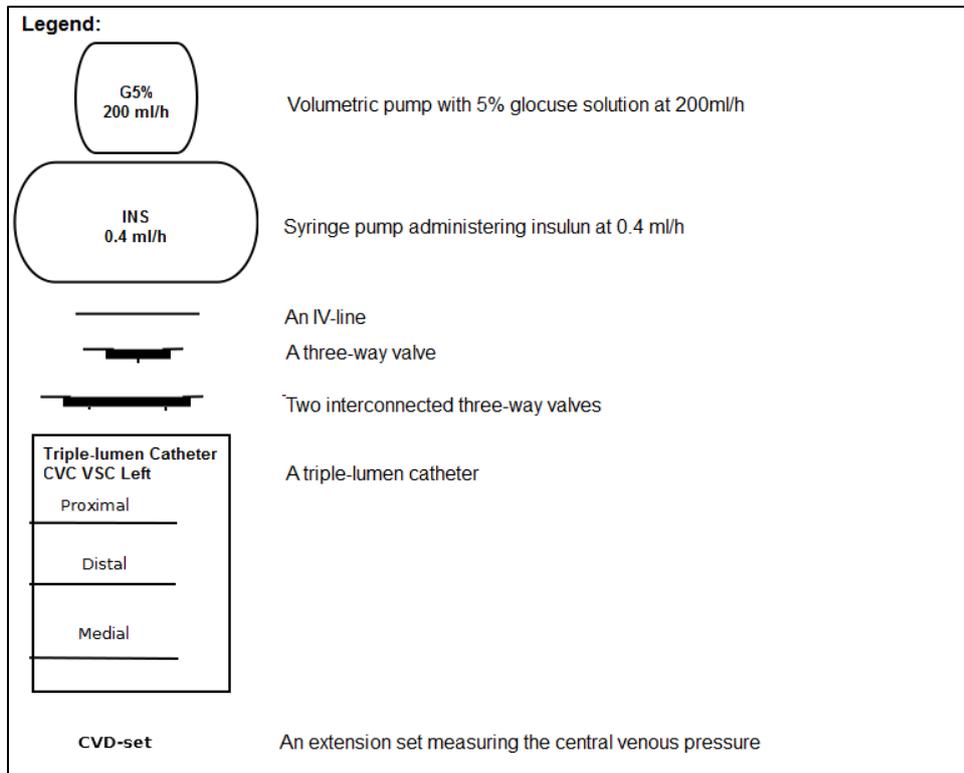


Figure 28: Legend for the IV tubing forms.

Table 7: Abbreviations used in the IV tubing schemes.

Abbreviation	Meaning	Abbreviation	Meaning
CVC	Central venous catheter	INS	Insulin
VJ	Vena jugularis	NOR	Noradrenalin
VSC	Vena subclavia	DOPA	Dopamine
VF	Vena femoralis	MID	Midazolam
PIV	Peripheral IV catheter	MORF	Morphine
A	Arm	KAL	Kalium (potassium)
B	Been (Leg)	MAG	Magnesium
H	Hand	MIL	Milrinone

V	Voet (foot)	VASO	Vasopressin
L	Left	G5%	Glucose 5%
R	Right	NaCl	Natrium (Sodium) Chloride 0.9%
TACRO	Tacrolimus	AMIO	Amiodarone
HYDO	Hydrocortison	PROP	Propofol

Volumetrische pompen:

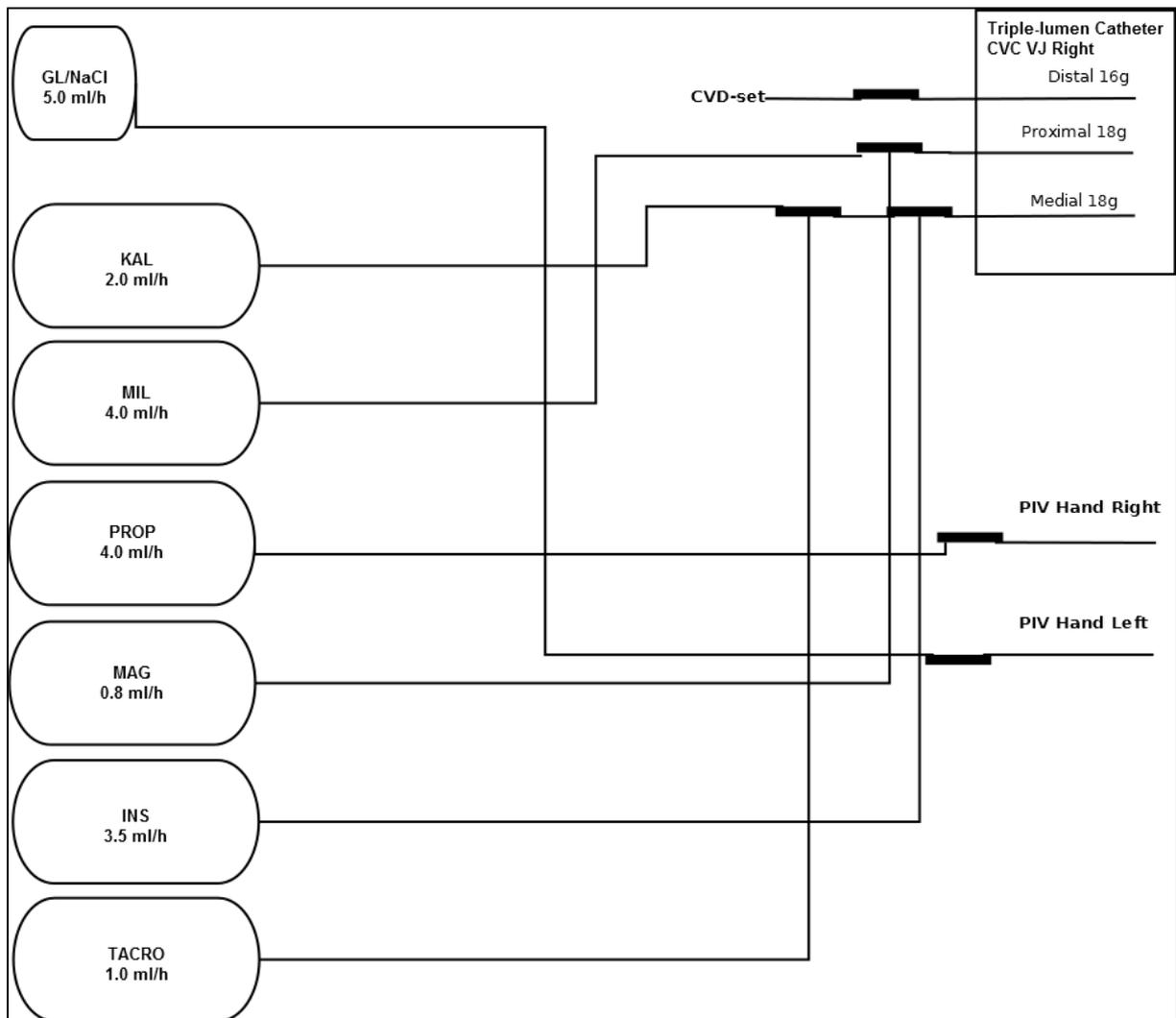
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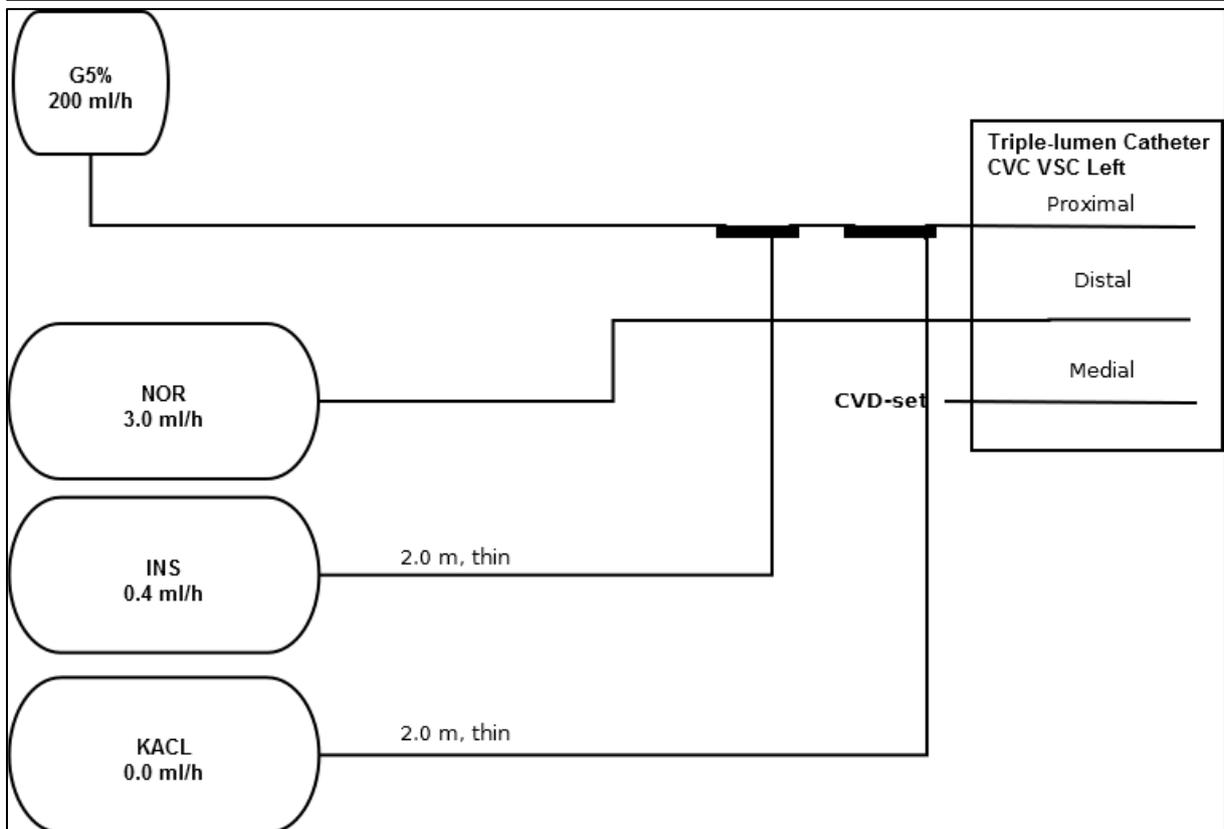
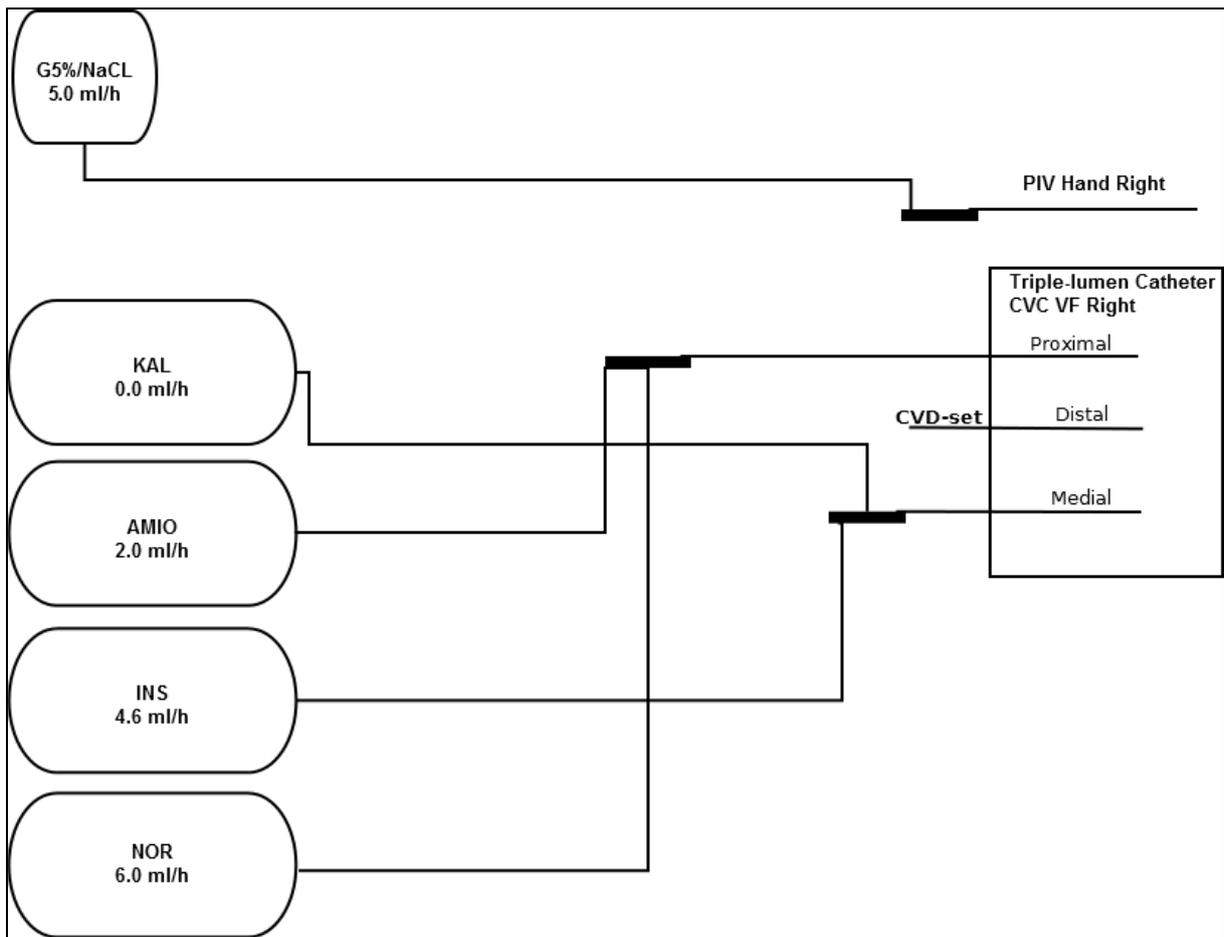
Spuitpompen

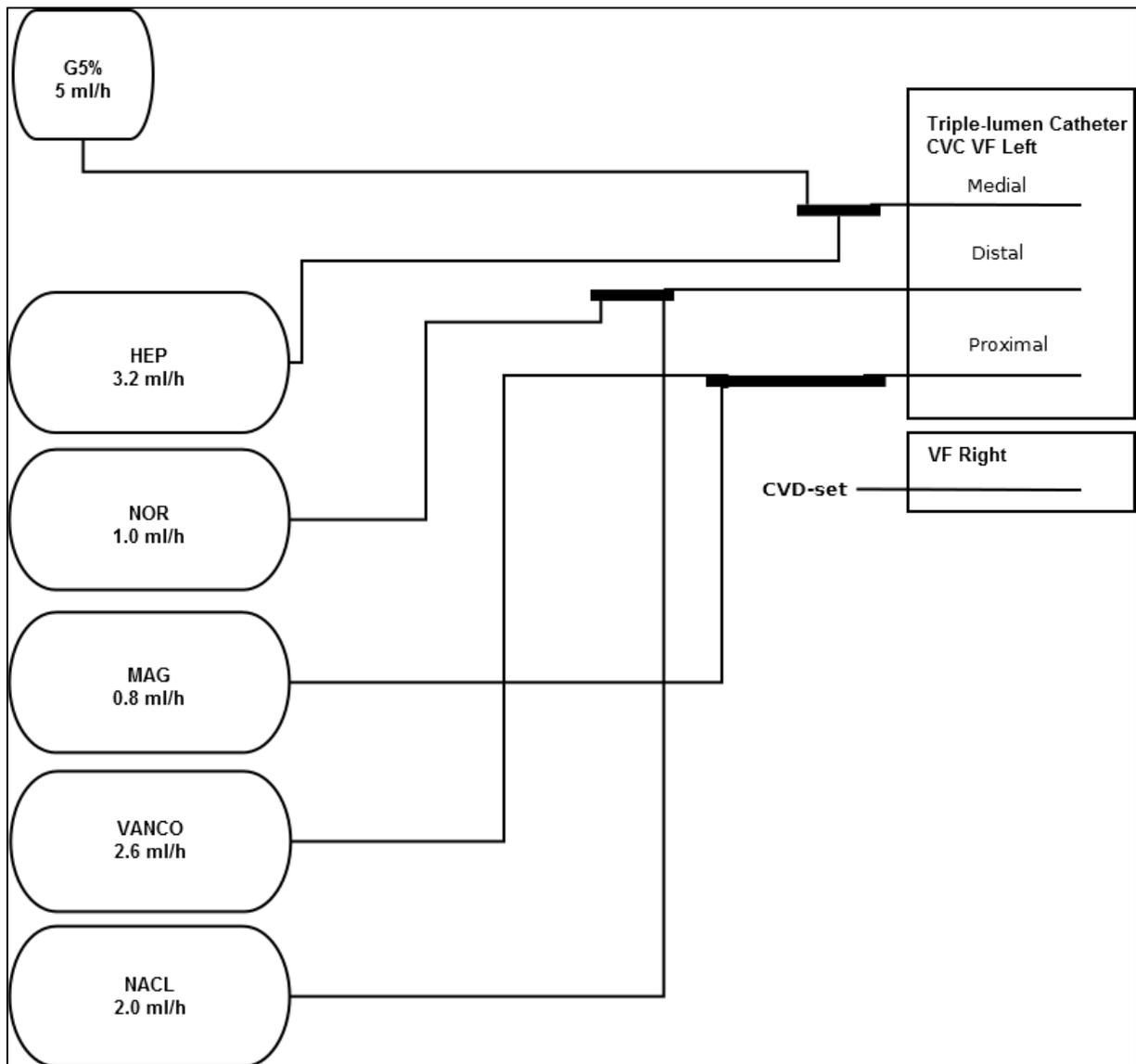
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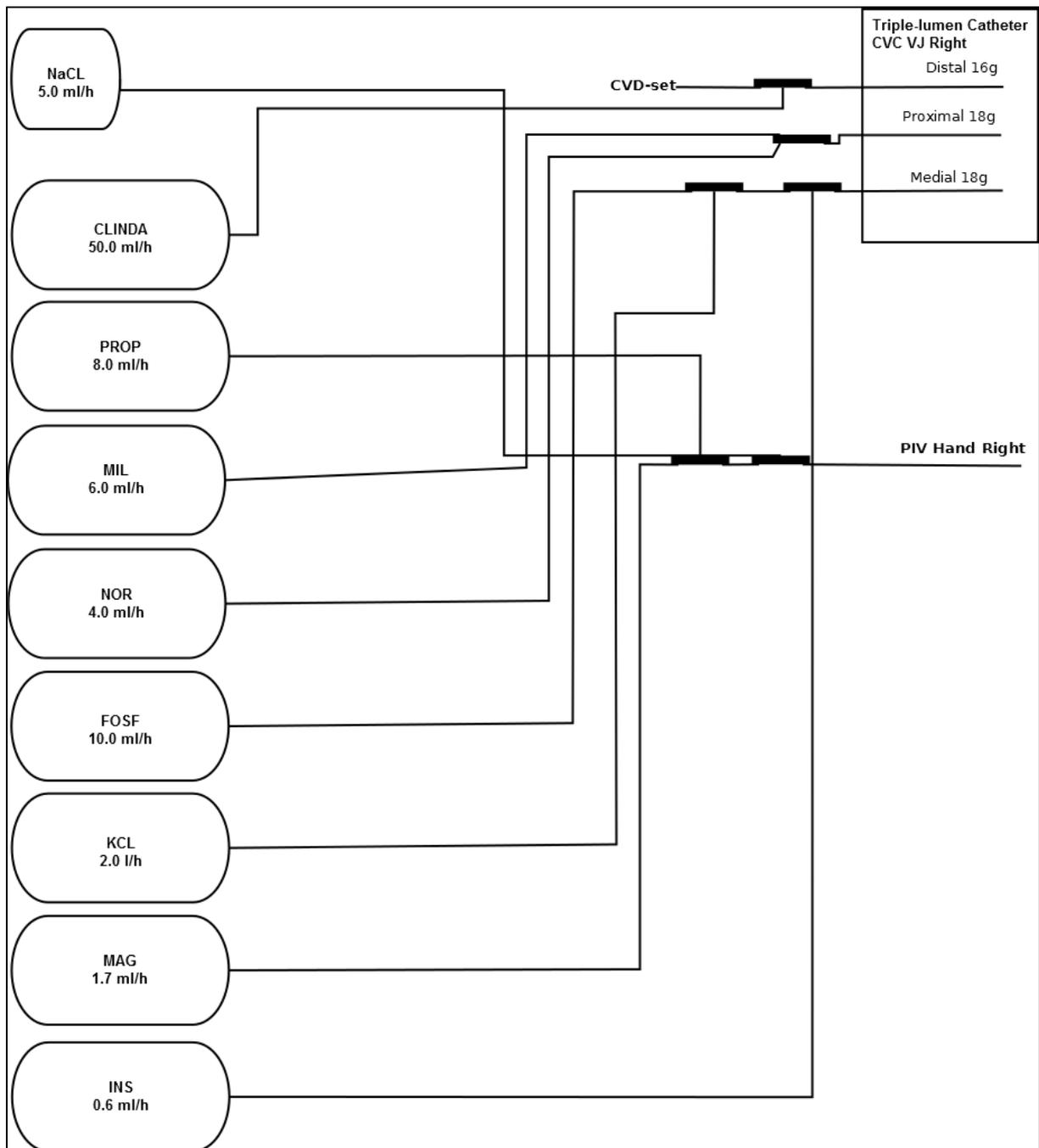
Type catheter + locatie + kant

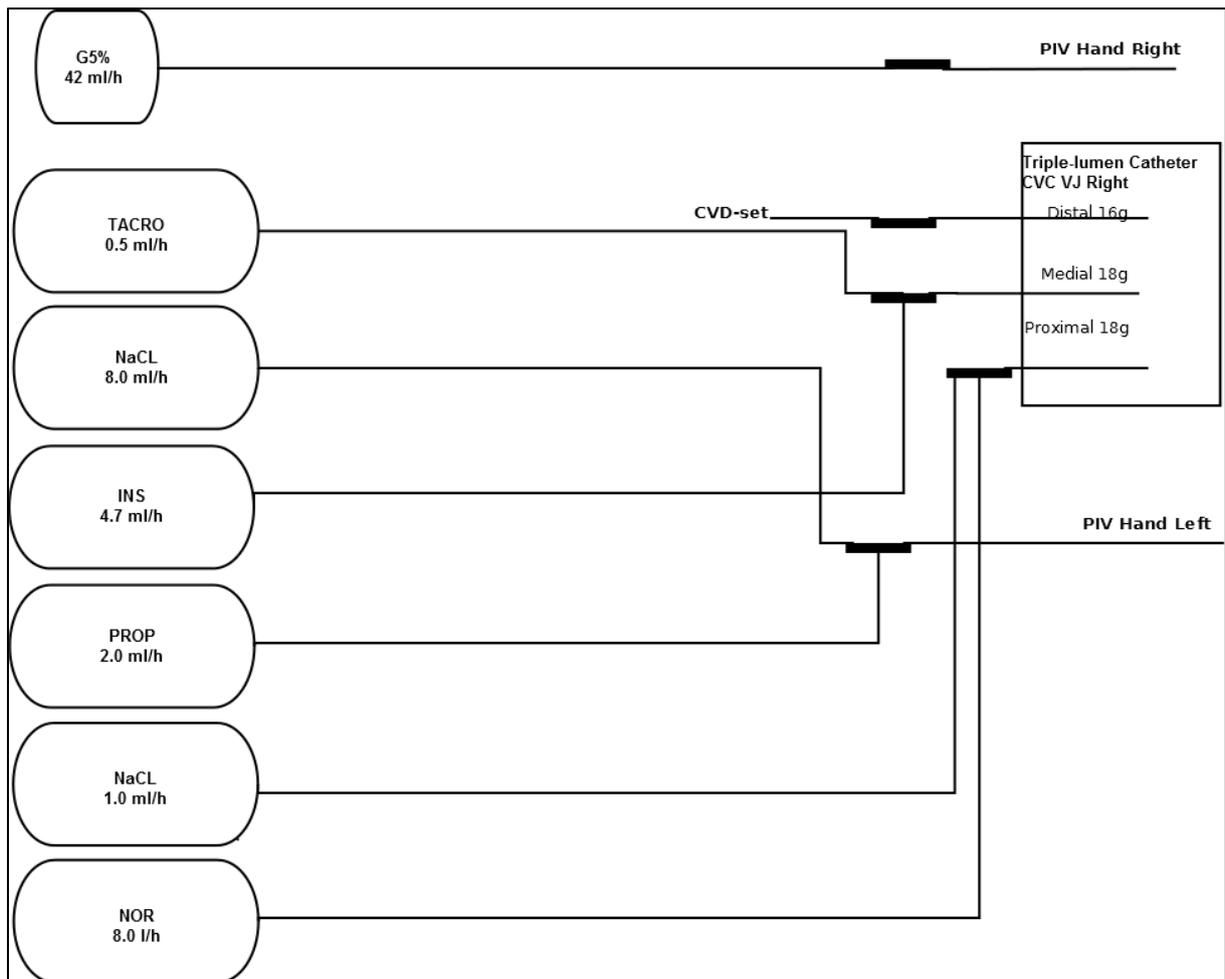
Figure 29: The infusion form which was used as a template for drawing out an IV tubing

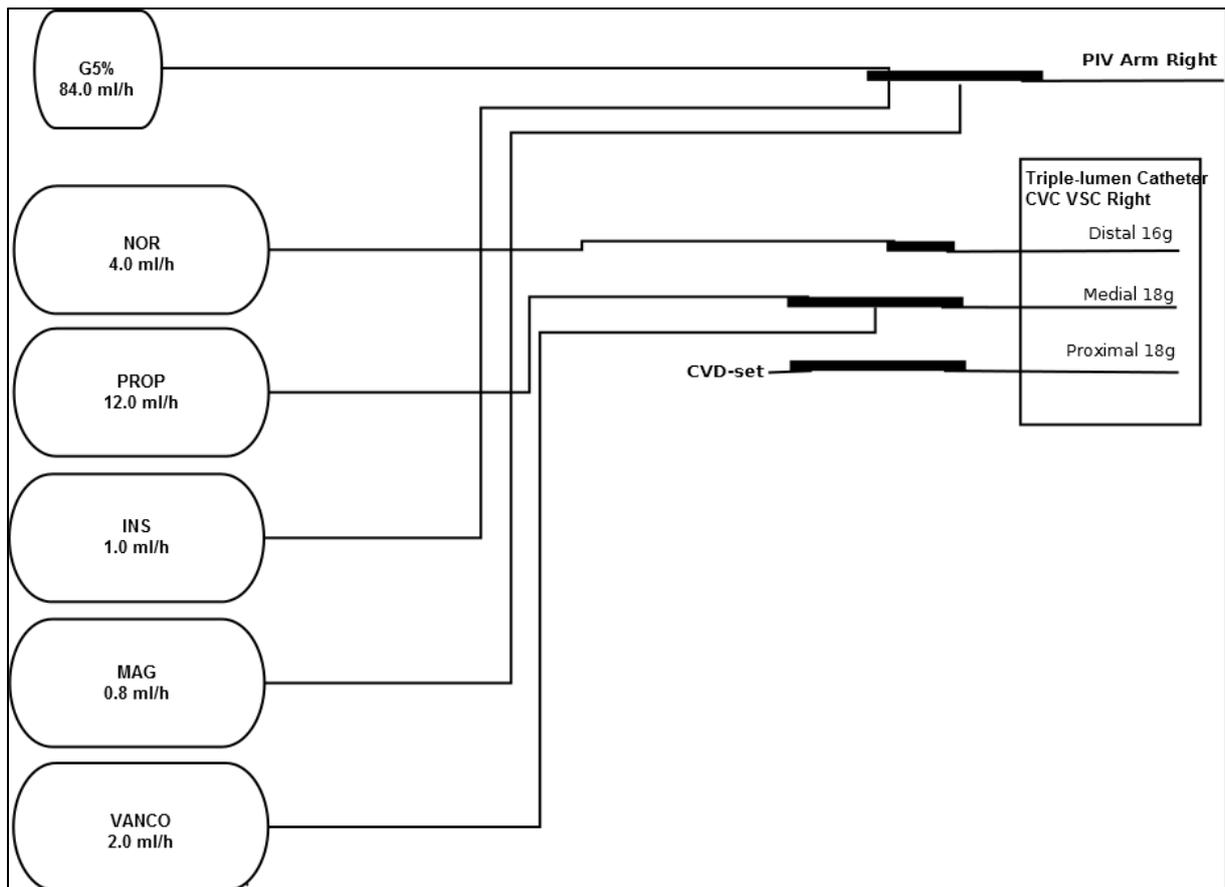


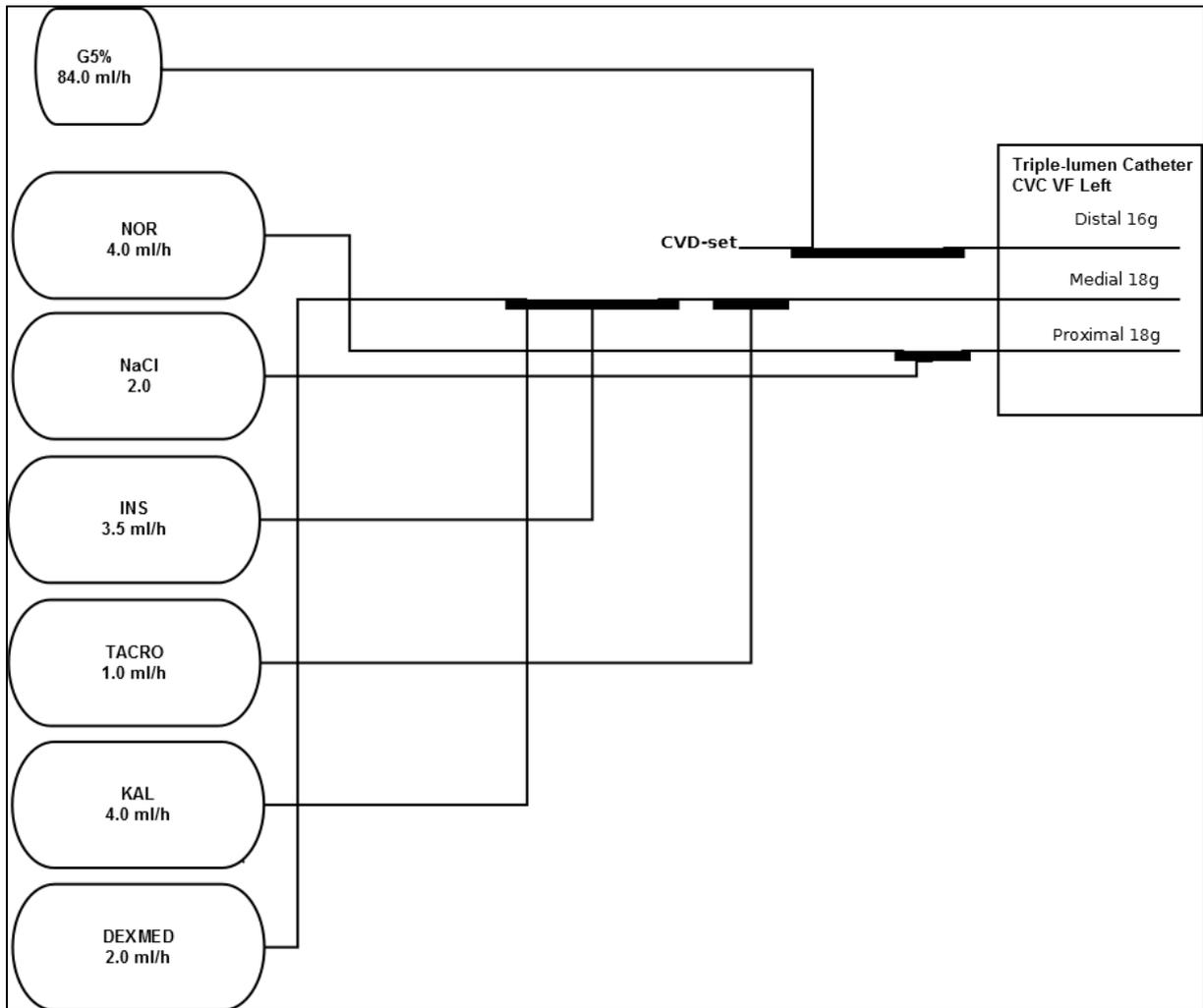


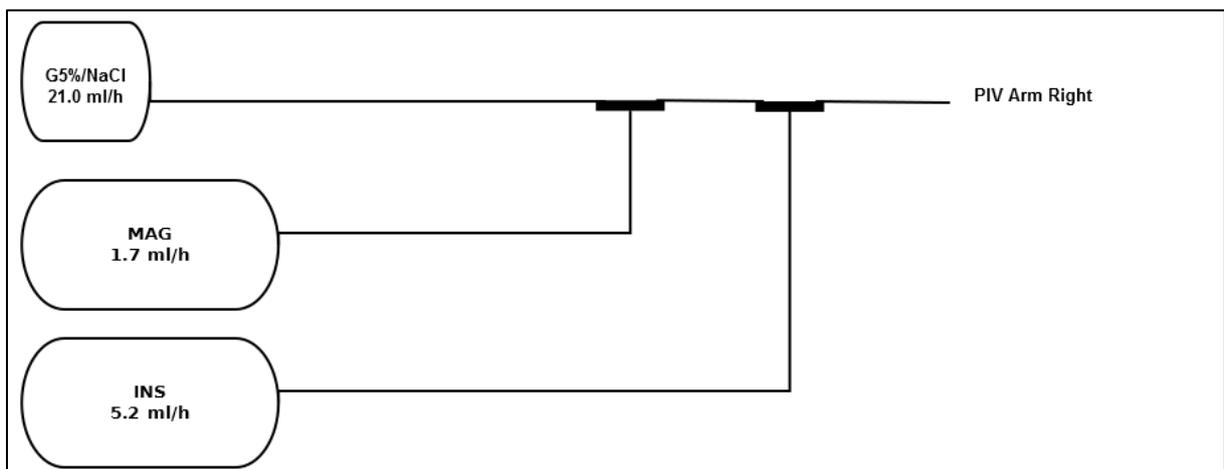
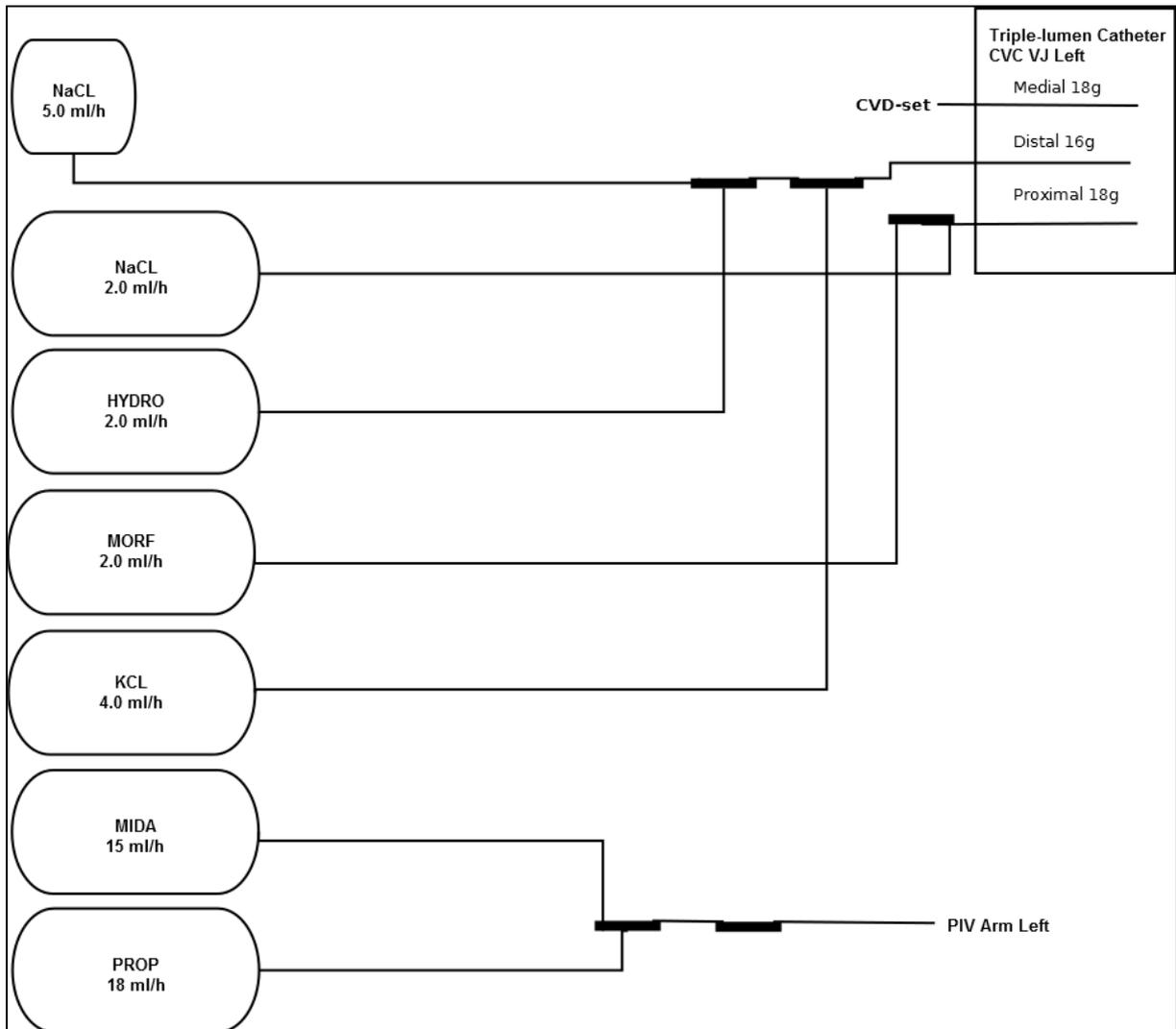


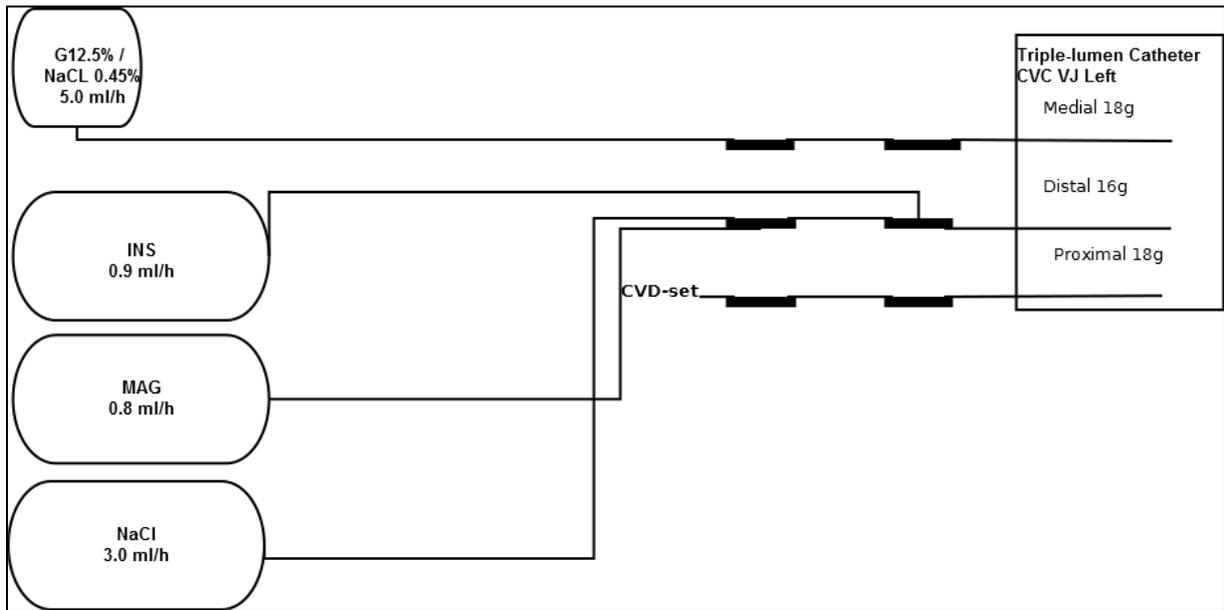












Appendix F: Multiplex User Interface

Below you will find screenshots of the user interface of the Multiplex Infusion System.

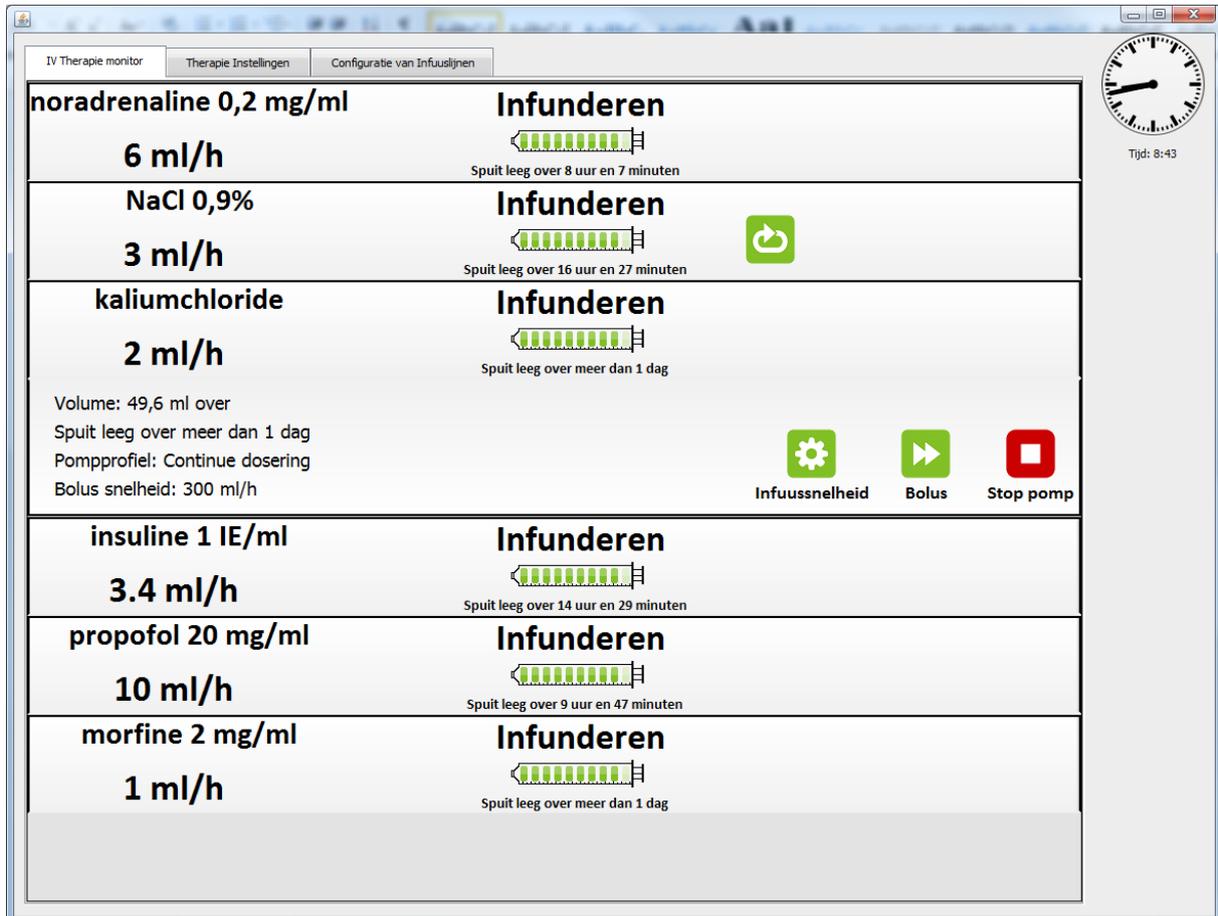


Figure 30: The main screen of the Multiplex interface.

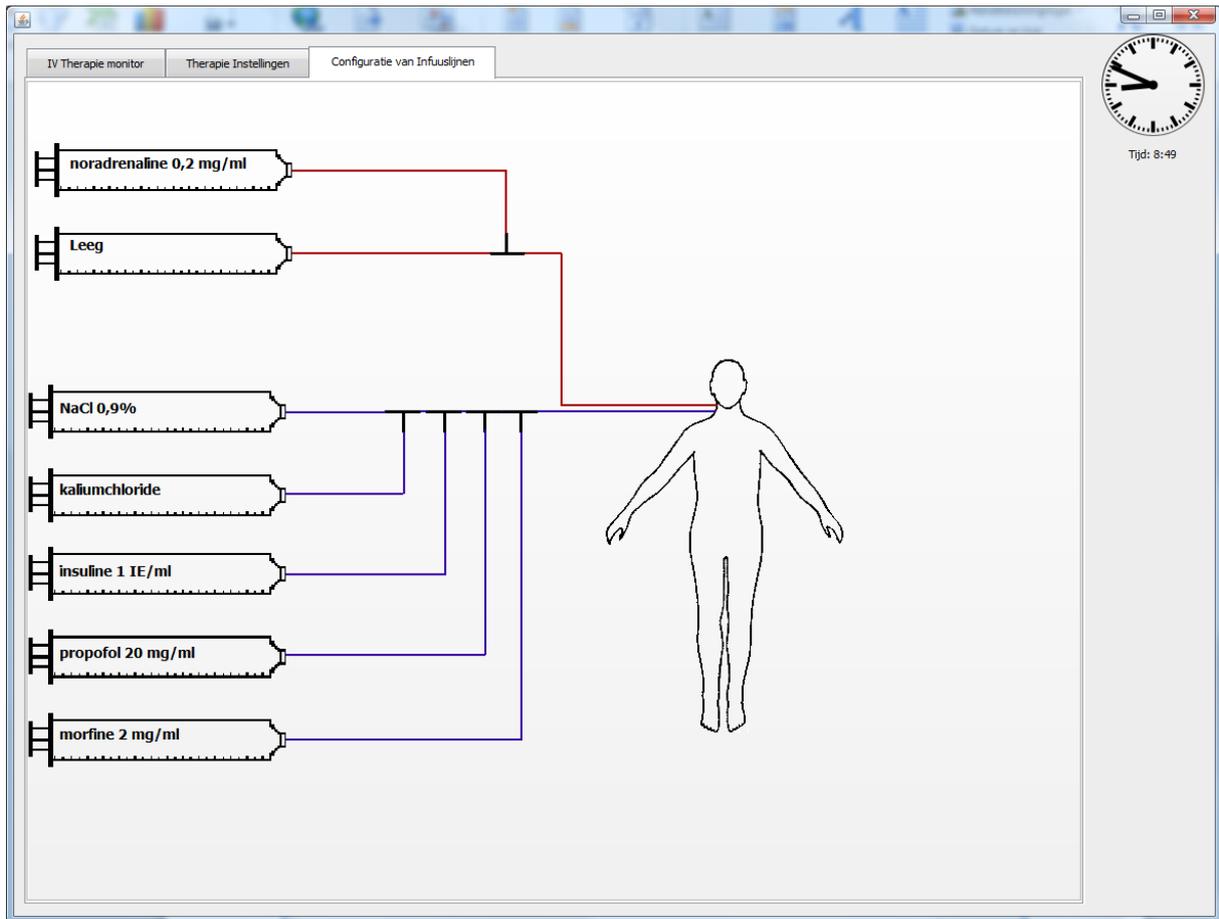


Figure 31: The IV tubing tab. This screen displays the tubing of the IV system.

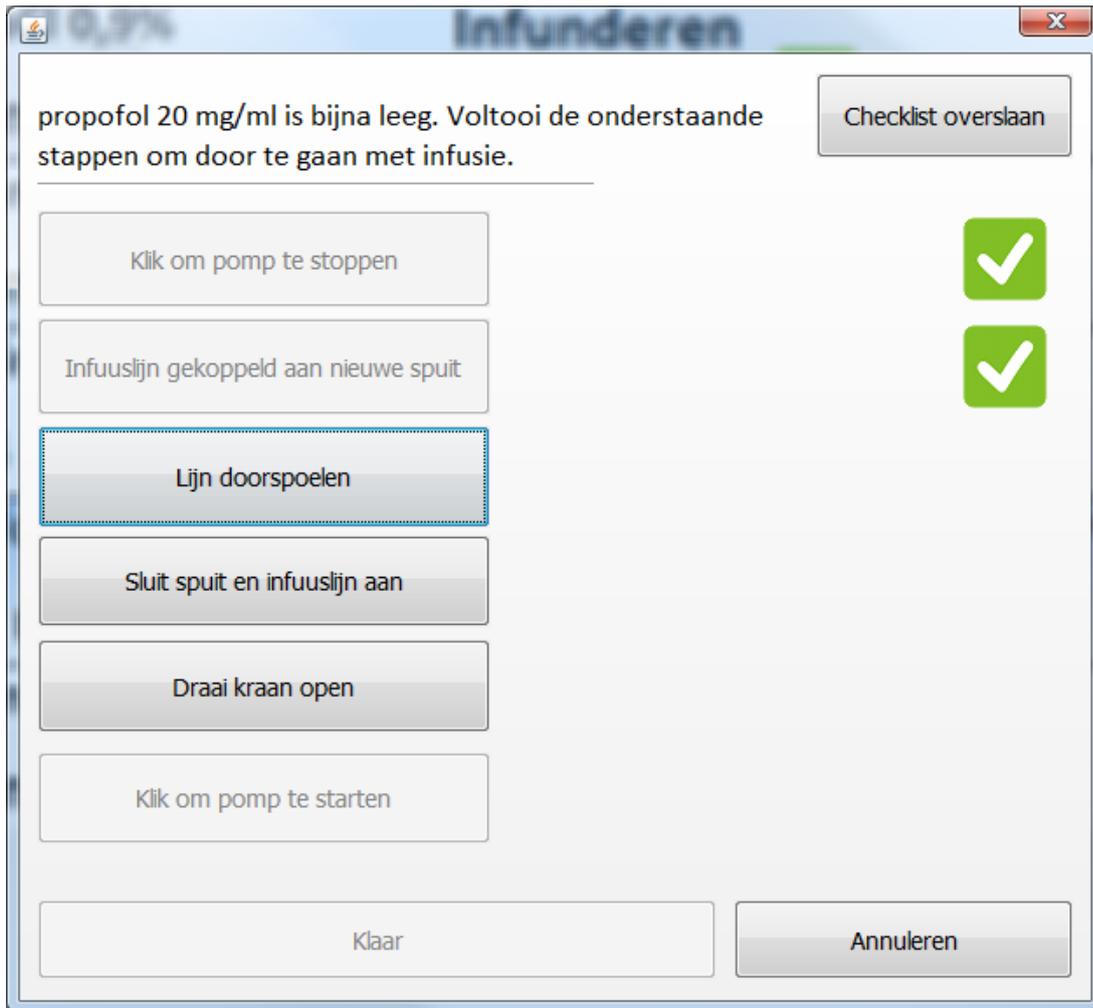


Figure 32: A checklist which can be used when replacing an empty syringe. It is possible to skip the checklist using the button in the upper-right corner.



Figure 33: A dialog asking the user permission to change the administration rate of morphine.