Designing a low-fi laparoscopy simulator for studying learning of complex motor skills.

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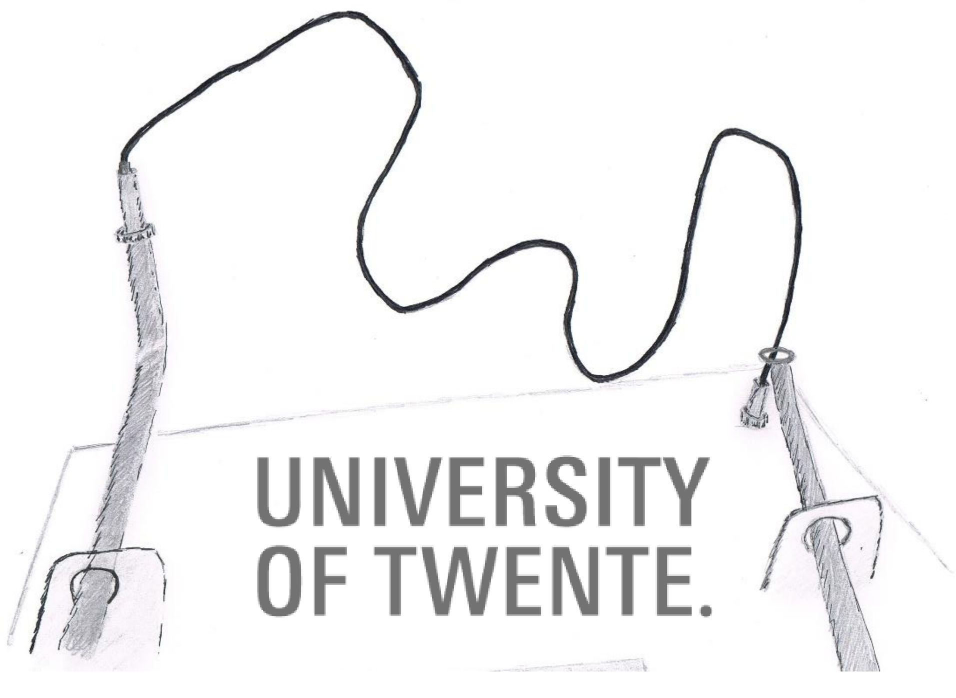

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Abstract

This paper describes the development of the Buzz Wire Simulator, an economical low fi laparoscopy simulator.

Design objectives: The design requirements and objectives derived from the literature are described to pursue resemblance with existing leading laparoscopy simulators. Thirteen design requirements have been established. Essential requirements to create a resembling complex motor task are: Low Cost, Assessable, Configurable Error Rate, Virtual Reality, Visuo-Spatiability, Bimanuality, Hand-Eye coordination and Configurability and Flexibility. Other requirements are: 2D / 3D translation and rotation, Reduced / Disturbed tactile feedback, Steadiness, Stick-Slip phenomenon and Fulcrum Effect.

Simulator design: The Buzz Wire task (Kaschub, 2016) is chosen as basic design principle. This task fulfills eight design requirements, six of which are categorizes as 'Must'. Two prototypes led to the design of the Buzz Wire Simulator. The current design uses a so-called 'Arduino' which is built into the simulator to generate and display data. All essential design requirements are implemented successfully, in an economical way.

Design evaluation: To gain insight into the performance and the functioning of the Buzz Wire Simulator, a validation research has been conducted. The results show that the respondents learn, this raises the opportunity to explore individual learning curves. The results also state that the design resembles the LapSim Simulator to some extent. It can be concluded that the Buzz Wire Simulator can be used for research into learning curves concerning complex motor tasks (laparoscopy).

Design criticism: Although there is sensitive network on wires on the inside, the simulator proved robust and there were no problems with neither the software nor the hardware. Firstly, the difference in bimanuality between the participants was remarkable. Some respondents often limited themselves to just moving the right hand (Ring). Others used both hands, effectively or not. Recommend is to discover the fluent motion pattern. In addition, the nature of the variable 'errors' was more complex than it seemed, and extra attention is needed for the error percentage variable; The percentage of the trial time that the ring was in contact with the wire

Keywords: Buzz Wire Simulator; Simulator Design; Laparoscopy; MIS; Learning curves; Complex motor procedure

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Introduction

The first and main goal of this research is to develop a low-fi laparoscopy simulator for studying learning of complex motor skills. A simulator which resembles an existing, leading high-fi laparoscopy simulator and therefore also resembles a laparoscopy procedure. Laparoscopy, a minimal invasive surgery (MIS) has been defined as an abdominal surgical procedure using endoscopic tools and a camera inserted through incisions in the abdominal wall (Cao, MacKenzie & Payandeh, 1996). Learning laparoscopy is a complex and complicated process involving various cognitive, perceptual, motor and technical skills (Cao, MacKenzie & Payandeh, 1996; Kaschub, 2016; Matern & Waller, 2014). As stated, the aim of the simulator is to study learning of complex motor skills. Studying learning is done by analyzing individual learning curves. A learning curve is defined as a mathematical association between training amount and performance. This association is often a graphical depiction of how a person learns about a subject (Jonassen & Grabowski, 2012). Learning laparoscopy through simulation is a viable alternative to other methods such as apprenticeships. This is particularly true as it obviates students from the consequences of performing under pressure caused by, for example, time. A range of benefits are associated with virtual simulator-based laparoscopy research which suggests that its use in research institutions is almost an imperative (Anastakis, 2000; Schreuder, 2001). However, the high costs associated with implementing virtual simulator laparoscopy research precludes its extensive use. There is therefore an urgent need for an inexpensive / economical virtual simulator solution for research into the learning of laparoscopy (Lehmann, Grone and Lauscher, 2012).

The objective of the literature review is to derive design objectives for an effective low-fi laparoscopic simulator. Firstly, laparoscopy and learning curves will be defined. This is followed by a review of literature on key factors impacting learning curves related to laparoscopy. This review will be the basis for the design objectives and requirements. The second chapter describes the design of the low-fi laparoscopy simulator. The most suitable principle is selected and configured into a low-fi simulator which meets as many as possible design requirements. The second goal of this research is to evaluate and validate the designed simulator. A validation study and its results and conclusions will be described in Chapter 3. Chapter 4 provides design criticism and recommendations based on the results and experiences of the evaluation and validation research.

1. Design objectives

This chapter starts with a review of literature on key factors impacting learning and appurtenant individual learning curves related to laparoscopic motor skills. In addition, the literature on the impact of time pressure on individual learning curves is reviewed. Thereafter, this literature review is being used to derive the key requirements that impact designing a low-fi laparoscopy simulator for studying learning of complex motor skills. The derived design requirements and objectives are described to pursue resemblance with existing leading laparoscopy simulators. In the end, thirteen design requirements have been established.

1.1. Background

The literature reviewed in this paragraph is a basis for the design objectives and requirements. Some of the design requirements which have been derived, are stated beneath sections in this paragraph. These design requirements are further discussed in paragraph 1.2. and summarized in figure 3.

1.1.1. Definition laparoscopy

Laparoscopy or minimal invasive surgery (MIS) has been defined as an abdominal surgical procedure using endoscopic tools and a camera inserted through incisions in the abdominal wall (Cao, MacKenzie & Payandeh, 1996). This contrasts with traditional surgery where the operated region must be cut open to be accessible to the surgeon. Minimal invasive surgery (MIS) offers many advantages over conventional surgery including superior cosmetic results due to smaller scar marks, less post-surgery pain, quicker discharge of patients and faster recovery (Matern & Waller, 2014; Ponsky, 1991).

However, learning laparoscopy is a complex process because it requires the surgeon to have cognitive, perceptual, motor and technical skills (Cao, MacKenzie & Payandeh, 1996; Kaschub, 2016; Matern & Waller, 2014). This is due to the differences between regular surgery and laparoscopy. Successful laparoscopy depends on the physician's diagnostic capability using 2D images projected on screen, the inverted / indirect use of instruments that require physicians to adopt different postures that can cause physical discomfort and move instruments along a fixed axis* (Groenier &

Schraagen, 2014). Furthermore, the number of complications in laparoscopic treatments is inversely proportional to the experience of surgeons implying that much experience is required for a successful laparoscopic surgery (Gallagher & Smith, 2003). These views suggest that laparoscopy is more difficult and riskier to perform than regular surgery.

Laparoscopy requires niche skills and hence is more demanding to learn than non-minimally invasive procedures (Palep, 2009). The many advantages of laparoscopy imply that it is important to identify all possible factors that impact the learning curve of surgeons who are learning about laparoscopic procedures.

*Design Requirement 1. 2D / 3D Translation & Rotation

1.1.2. Definition learning curves

A learning curve is defined as a mathematical association between training amount and performance. This association is often a graphical depiction of how a person learns about a subject (Jonassen & Grabowski, 2012). The graph is plotted with experience on the 'X' axis and 'Performance' on the 'Y' axis. In general, the learning curve is characterized by a drop followed by a plateau. The steeper the drop the shorter the time taken to learn a subject. A shallow curve indicates a longer learning period and is an indicator of the person's ability to learn complicated motor processes required for complex tasks such as those involved in laparoscopy (Kaschub, 2016). Figure 1 depicts a schematic example of a learning curve. The number of trials is shown on the x-axis and the trial duration on the y-axis. The amplitude represents the learning effect and the asymptote the expected maximum performance. A fictitious number of trials are shown with a corresponding imaginary smoothened learning curve.

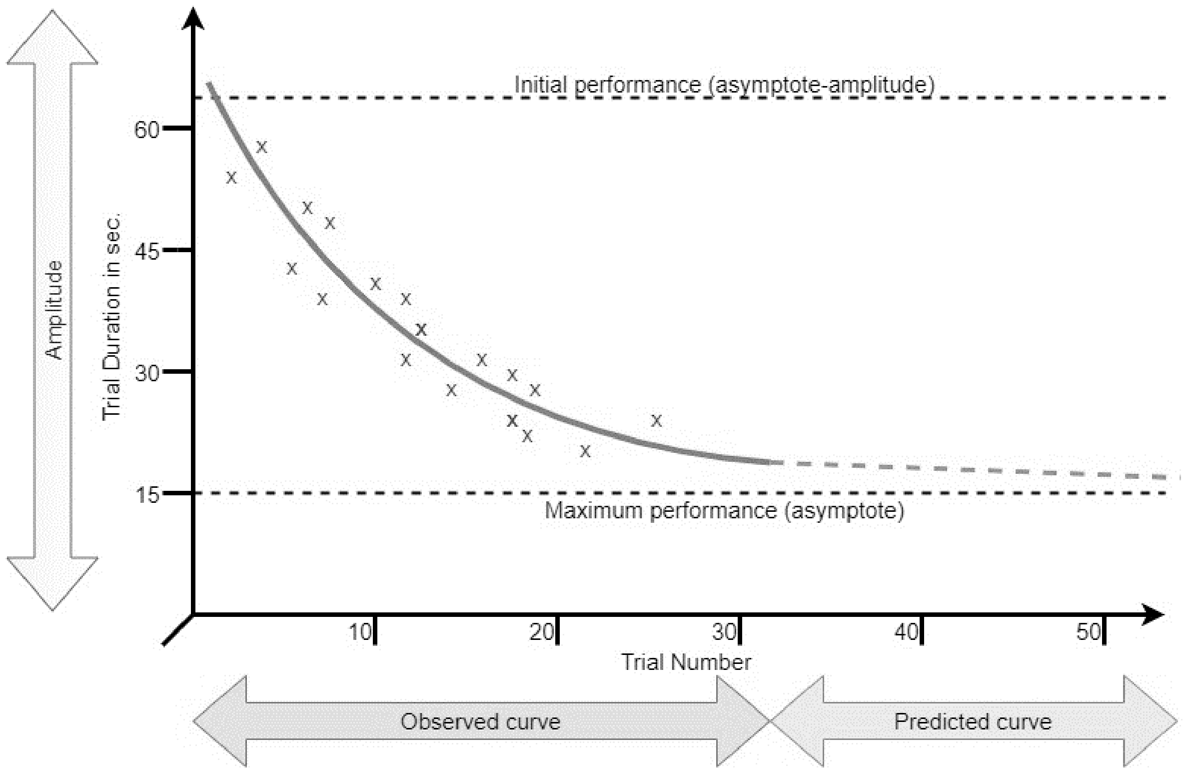

Figure 1. *Learning curve example.*

1.1.3. Impact of cognitive factors on learning curve

Various studies have been done to evaluate the impact of cognitive and psychomotor factors on the learning curve of laparoscopy surgeons. It should be noted that not every research uses the concept 'Learning Curves' in the strict sense as it is used in this study. For the studies used it is assumed that their conclusions on their (slightly) deviating concept of 'Learning Curves' have similar effects. Research by Buckley, Kavanagh, Nugent and Ryan (2014) & Groenier and Schraagen (2014) established that differences in cognitive ability impacted changes in learning curves. Sippel (2013) showed that novices with higher cognitive ability had a steeper learning curve than their counterparts who exhibited lower cognitive ability. Keehner et al. (2004) and Luursema (2010) found that students with higher levels of visualization, perception speed, visual memory and spatial orientation had steeper learning curves. Studies by Hedman et al. (2007) found that persons with higher visuo-spatial ability required lesser time to complete surgical procedures involved in laparoscopy. These studies were corroborated by earlier research by Hedman et al. (2006) who observed that higher visuo-spatial ability resulted in steeper learning curves related to laparoscopy procedures and that this correlation was higher for higher complexity of procedures*.

*Design Requirement 2. Visuo-Spatial Competencies

Impact of psychomotor factors on learning curve

Similar research was done on the impact of psychomotor abilities of laparoscopy surgeons on learning curves. Studies by Van Herzeele et al. (2010) found that motor dexterity was a significant predictor of learning curves related to ambidexterity*, depth perception and the ability to work even with reduced tactile feedback*. The correlation between higher motor dexterity and a steeper learning curve related to laparoscopy surgery proficiency was also established by the research of Gallagher and Smith (2003) & Gallagher, Leonard and Traynor (2009). The above findings indicate that not only cognitive and psychomotor skills are significant predictors of the learning curve, but also that sufficient research has been done on the impact of these factors on the ability of student doctors to learn laparoscopic skills.

*Design Requirement 3. Ambidexterity / Bimanual

*Design Requirement 4. Reduced / Disturbed tactile feedback

Research gap

However, there is a lack in research on the impact of time pressure on learning curves of laparoscopy students who must learn complex motor procedures to perform such surgery effectively. Pusic, Brydges and Kessler (2014) observed that the role of time pressure in the teaching of complex motor procedures involved in surgery has not been investigated in detail. It is this gap in the literature on the pedagogy of laparoscopy that might be bridged by the use of a low-fi simulator. This need for a low-fi simulator is justified by the observations of Anastakis (2000), Francis, Hanna, Cresswel and Carter (2001) and Schreuder (2001) that excellence in laparoscopy is not dependent only on prior experience, cognitive or psychomotor ability but on a whole host of factors which are yet undetermined. This research proceeds from the assumption that time pressure is one of the factors to explore.

Impact of Fitts Law

According to Mackay (1982), medical practitioners are always under pressure to increase speed of performance without compromising the quality of care or the number of errors made. The trade-off between speed and accuracy or quality in surgical procedures requiring complex motor procedures is governed by Fitt's law according to which accuracy is inversely proportional to speed of performance for a task keeping its difficulty level constant (Heitz, 2014). That is, the lower the speed the greater is the accuracy of the performance of complex motor tasks. Extending Fitt's law to the pedagogy of learning surgical motor skills however has yielded inconclusive results.

Studies by Zelaznik, Spencer and Doffin (2000) suggests that time pressure results in steeper learning curves even among students with differing motor skill abilities. However, this study did not examine accuracy levels of the surgical procedures learnt by students. Studies by Beiloc et al. (2008) found that time pressures cause novices to make more mistakes but improves the accuracy of experts. This implies that past experience significantly mediates the trade-off between speed and accuracy.

Recent research by Becca, Buckarma, Cook and Farley (2018) on novice medical students, junior and senior residents yielded mixed results with respect to Fitt's law. Novice medical students were able to maintain / improve their accuracy even with increased speed, thereby positively violating Fitt's law. Junior residents followed Fitt's law in that they displayed no significant changes in accuracy levels with increased speed while the senior residents negatively violated Fitt's law in that attempts to increase speed results in greater than expected error rates. These findings corroborate those of Beiloc et al. (2008) as it suggests that Fitt's law is observed or even positively violated for learning curves involved in performing repetitive motors tasks which the student is already familiar with but that Fitt's law gets negatively violated at the asymptote of the learning curve for repetitive tasks and when new tasks have to be learnt and performed at a faster pace.

Impact of the emphasis of learning interventions

The emphasis of pedagogic interventions, such as complex motor tasks, can also mediate the speed-accuracy trade-off for learning curves as laid down by Fitt's law. Studies of baseball novices by Southard (1989) found that an emphasis on accuracy lead to the novices constraining their arm movements that ultimately negatively impacted their development of an accurate swing. When speed was emphasized, the students developed a swing that combined speed and accuracy. This suggests that pedagogic emphases can impact those cerebral systems that control the learning of motor skill activities and that for some motor skills it would be more effective to emphasize speed.

Impact of the type of pedagogic intervention

The type of pedagogic intervention used also plays an important role in impacting the effects of time pressure on the learning curves of laparoscopy students. Conventionally, students of laparoscopy have been trained using apprenticeship formats with practical training in the operating room (Botden & Jakimowicz, 2009). The key disadvantage of this method is that students do not have the opportunity to practice the actual movements required in laparoscopic surgery (Sun, Xie & Zheng, 2017). To overcome the disadvantages of apprenticeships, in recent times, several training methods have been introduced including box training, hybrid simulation, laboratory animals, cadaver models, virtual reality simulators and augmented reality simulators (Yiannakopoulou, Nikiteas & Perrea, 2016).

Of these methods, it is the virtual reality laparoscopic simulators that are widely considered to have the best potential to effectively train students of laparoscopy* (Yiannakopoulou et al. 2016). In this method of training, various skills that the student would require in real life operations are learnt through computer-enabled simulations. The student interacts with various elements in the learning environment, that resemble real-life scenarios and provided with the means to change or adjust according to the required level of performance (Iwata, Fujiwara & Kodera, 2011). Furthermore, simulation offers the opportunity of learning without using real patients. This means that virtual reality simulations provide students with a risk-free learning environment to learn complex and critical procedures that occur during laparoscopic interventions. Virtual reality simulations provide training in basic skills in a learning environment that is free from pressures of operating on a real patient (Perrenot, Perez & Tran, 2012). They can provide more objective performance assessment on the student's acquisition of those psychomotor skills required for specific laparoscopic tasks. Despite these advantages however, laparoscopic training using virtual reality simulation is not much used in laparoscopic training because of the considerable investments required (Yiannakopoulou et al. 2016). Furthermore, its effectiveness as a training tool still needs to be evidenced to justify such high investments.

*Design Requirement 5. Virtual Reality

The above findings were corroborated by the even earlier research of Andreatta, Woodrum and Birkmeyer (2006) who observed that laparoscopy surgeries are unique, complex and complicated and takes too much time to learn. There is a need for surgeons to shorten their learning curves and be able to operate as fast as possible. There is an urgent need for computer-aided laparoscopic simulation-based training to improve the efficiency of training. Andreatta et al. (2006) used the LapMentor simulator to demonstrate the effectiveness of virtual reality based training. It was found that training using LapMentor lead to quicker skill acquisition among residents and better performance in the operating room. However, the LapMentor simulator was found to be expensive and hence its used had to be validated and justified before introducing it to training programs.

Lehmann, Grone and Lauscher (2012) also evaluated the suitability of virtual simulation for training purposes among 36 laparoscopy course students in Warnemuende, Germany. There were 15 simulation sessions conducted over 5 days that measured student performance against 16 individual parameters. It was found that simulator training was very well accepted by the institute as most students had limited training opportunities in their respective hospitals. However, the research concluded that simulator-based interventions were currently too expensive to be used in long-term laparoscopy training courses*. Experiments by Zendejas, Brydes and Hamstra (2013) showed that laparoscopic skills can be acquired more effectively through simulation – based training interventions rather than through practical assessments conducted during clinical training. It was found that the virtual simulation-based training reduced operating time, enhanced student ability to implement surgical techniques, immediately apply skills on patients in the operating rooms, provided students with better performance scores and reduced intraoperative and postoperative complications (Zendejas et al. 2013). However, implementing virtual reality solutions in training institutes was found to be very expensive. Zendejas et al. (2013) indicated the need for more favourably priced virtual – simulators in laparoscopic training programs.

*Design Requirement 6. Low Cost

The above findings imply that a key factor in research on the impact of time pressure on learning curve of laparoscopy students can be virtual simulator-based interventions, if only the cost factor of such interventions can be reduced. Currently, the need for expensive virtual simulators in laparoscopic training interventions needs to be justified. Mandolfino, Sguanci and Minuto (2016) concluded that virtual simulators for laparoscopic training can indeed be constructed at economical costs.

Impact of error rate

Error rate made during the initial stages of learning motor tasks can also mediate the speed-accuracy trade-off in learning surgical procedures. Research by Zendejas, Ruparel and Cook (2016) found that errors made under paced learning conditions can result in a steeper learning curve and a more optimal speed-accuracy trade-off than correct performance*. This suggests that pedagogic interventions that emphasize the making and learning from errors during the initial stages of training in accordance with Fitt's law can be highly effective in generating a steep learning curve in the long – term.

*Design Requirement 7. Configurable Error Rate

Impact of pressure / expectations

Baumeister (1984) defined pressure in terms of an anxious desire for a person to perform well in a situation that is of importance to him / her. In an experiment that studied impact of expectation of performance on learning curves of baseball players, DeCaro, Thomas and Beilock (2011) found that pace of motor skill learning reduces under heightened expectation of performance. This phenomenon was termed 'choking under pressure' (De Caro et al. 2011). In situations of high pressure, the awareness of the person for good performance is increased and leads to explicit monitoring of motor skills required for the performance of a task. Such a sharp focus on the step – by – step tasks required to execute a piece of work disrupts the learning curves of proceduralized processes. In normal situations, where the person is not under pressure, proceduralized processes can be implemented without too much attentional control. However, the experiment of De Caro et al. (2011) indicated how under situations of pressure, proceduralized processes become subject to explicit monitoring resulting in a shallow learning curve. These findings suggest that when surgeons are pressurized to perform accurately in short time, expectation of better performance leads to explicit monitoring of proceduralized motor skill tasks such as those involved in laparoscopy leading to higher error rates.

Impact of worry about outcomes of performance

According to Beilock and Carr (2001), persons can be pressurized by situations where there is something significant at stake depending on the outcome of performance. Here the situation of pressure is created not by expectation of high performance but of worry about the consequences of low performance. In such a situation, a competition for attention results between the task that must be done on the one hand and worry about consequences on the other. Distraction of attention inhibits the performance of the working memory that governs the performance of proceduralized tasks (Gimmig et al. 2006). The working memory is consumed by irrelevant tasks – such as worry about consequences – resulting in sub-optimal performance of tasks to be done. These findings suggest that accurate performance of laparoscopic tasks depends on working memory which governs the performance of proceduralized routines. In a situation, where the surgeon must learn a proceduralized task in limited time, anxiety over performance outcomes can overwhelm the working memory thereby impacting his / her learning curve.

Impact of emotions

In a study conducted on golf players, Eysenck et al. (2007) examined the impact of emotion on the speed of learning motor skills involved in the playing of golf. The primary attention under circumstance of pressure is anxiety which was described as heighted states of emotional and motivational awareness. Persons with higher anxiety traits display higher levels of anxiety during normal situations and abnormally high anxiety during anxiety inducing situations, compared to persons with low anxiety traits (Mullen & Hardy, 2000). Anxiety impacts performance in two ways. Firstly, it consumes the resources of the working memory leaving less capacity for other tasks. Secondly, it induces the person to adopt compensatory strategies – such as explicit monitoring of sequence of tasks to be performed – that can inhibit the effectiveness of performance (Eysenck et al, 2007). The research of Eysenck et al. (2007) combines that of De Caro et al. (2011) & Beilock and Carr (2001) and implies that in situations of pressure – such as learning complex laparoscopy motor skills in short time – the emotional stability of the learner significantly impacts his / her learning curve.

1.1.4. Theoretical framework individual learning curves

Based on the above findings, the theoretical framework on individual learning curves in Figure 2 was developed. The core concepts of all sections are presented in a schematic way.

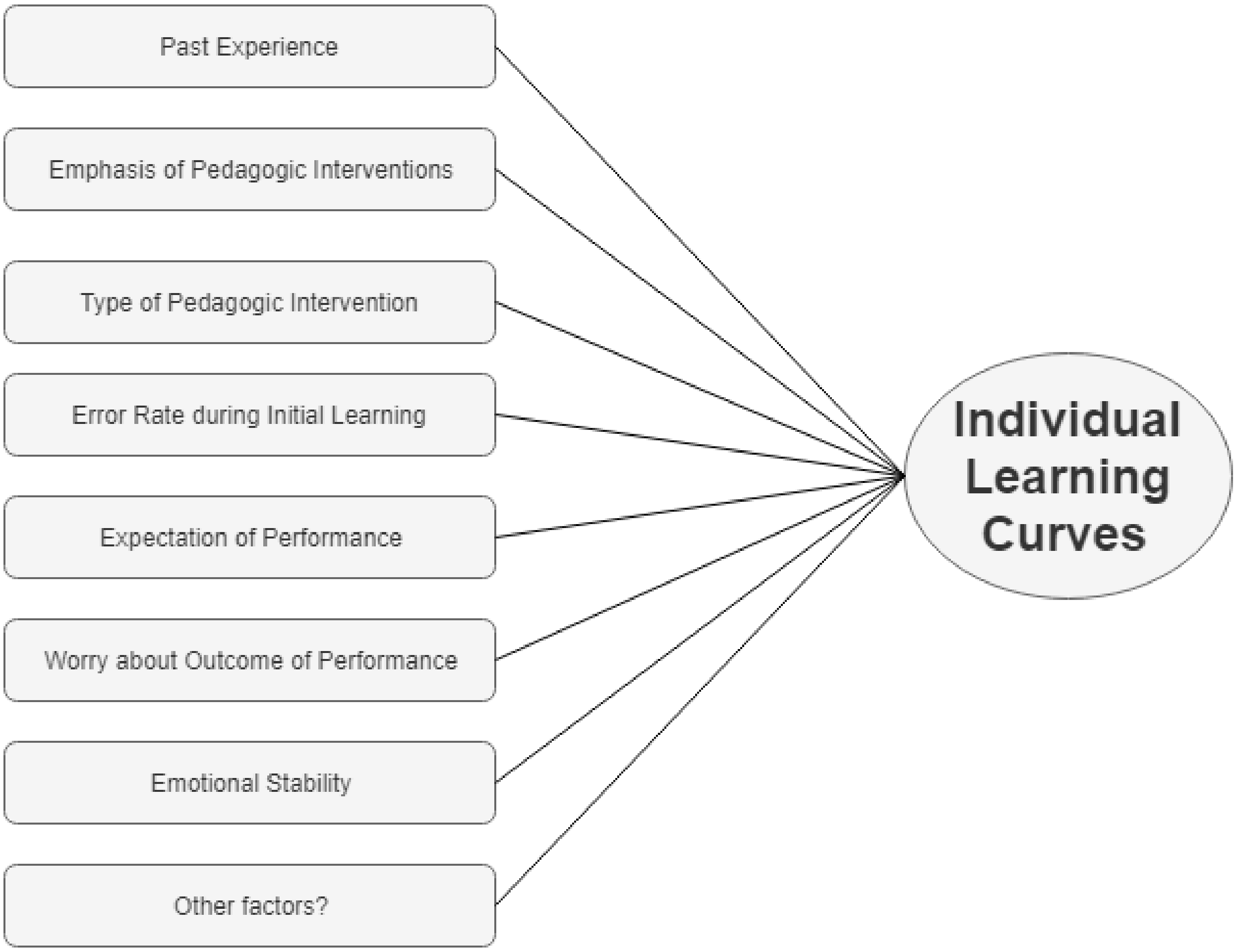

Figure 2. *Theoretical Framework Individual Learning Curves*

From figure 2, it is observed that experience impacts learning curve of laparoscopy surgeons, in other words this research assumes that the degree of novelty of the task determines the learning curve. The more new or unfamiliar a task, the shallower the learning curve. The more familiarity the student has had with the task or with associated tasks, the steeper the learning curve. There can be some laparoscopy tasks where the emphasis on speed can result in a steeper learning curve. Such tasks, however, need to be identified. Furthermore, allowing students to learn from their errors and implement these learnings in their training can result in steeper / more desirable learning curves (as well). The use of virtual simulators in laparoscopy training programs can play an important role in exploring the impact of time pressure on learning curves.

High expectations of performance – such as high levels of accuracy to be achieved from laparoscopy procedures in short time – can result in high error rates in performing proceduralized processes. Similarly, if students are unduly worried about the consequences or penalty of not achieving accurate results in short time, this can result in shallower learning curves. Personal factors such as emotional stability can also impact learning curves of laparoscopy students, where persons with higher levels of the anxiety traits can exhibit shallower learning curves under time pressure than those with lower levels of anxiety traits. These views suggest that students of laparoscopy must be provided with adequate counselling to mitigate the effects of speed induced expectations, worry and anxiety on their learning curves. There can also be other factors that impact learning curves of laparoscopy students not covered in this literature review, but which this paper can identify. For example, during the creation and validation of the simulator.

1.1.5. Conclusions literature review regarding individual learning curves

As stated, learning laparoscopy is a complex and complicated process involving various cognitive, perceptual, motor and technical skills. Because of this, the learning curve for laparoscopy surgeons can be far shallower than those required for other non-minimally invasive surgical interventions. It could be useful to evaluate the impact of time pressure on learning curves of laparoscopy students. From the findings in this chapter it can be concluded that there are various factors that can be leveraged to explore the impact of time pressure on learning curves. For example, reducing the emphasis of training interventions that often focus on accuracy during the educational process itself can affect the impact of time pressures on learning curves. It even might be the case that time pressure is beneficial to the learning curve. Similarly, mitigating the impact of error rate, of expectations from students, reducing worry and anxiety levels can work towards configuring the impact of time pressure on laparoscopy students.

However, the findings in this paragraph imply that possibly the biggest factor that laparoscopy training departments can leverage to explore the impact of time pressure is that of the training intervention itself. Rather than using traditional apprentice style methods of training or even modern equivalents such as box training, laboratory animals, cadaver models etc., it is the virtual simulator enabled training that holds the greatest potential to de-link student learning curves from time pressures. A range of benefits are associated with virtual simulator-based laparoscopy training which suggests that its use in training institutions is almost an imperative. However, the high costs associated with implementing virtual simulator laparoscopy training precludes its extensive use in training. There is therefore an urgent need to develop a low cost / economical virtual simulator solution for laparoscopy training. This research postulates that economical, virtual simulator-based laparoscopy training solutions will play an important role in exploring the impact of time pressure on learning curves of laparoscopy students.

1.2. Design requirements

The literature review presented in 1.1 derived some design objectives for an effective low-fi laparoscopic simulator. This paragraph allocates and prioritizes these and other design requirements.

1.2.1. Design requirements allocation

According to Arendt (2017) every design process for laparoscopic simulators should consider the concept of a resemblance spectrum. This spectrum provides a framework that enables testing the simulator being designed against actual laparoscopic procedures used in the operating room. The simulator must provide the student with a spectrum or range of low-fidelity to high-fidelity techniques to acquire the cognitive, technical and manual dexterity skills required for performing laparoscopic surgeries. Accordingly, the researcher considered a range of low and high fidelity-tasks in designing the simulator. Gallagher et al. (2009) observed that a key aspect of laparoscopic training is to teach students how movements of instruments in one direction causes a corollary movement of the instrument in the patient's abdomen and therefore on the visual display. This is called the Fulcrum Effect*. The implementation of this will be considered by the researcher during the design of the simulator. The insertion of an instrument in the patient's abdomen also might result in the presence of the 'Stick-Slip phenomenon'*. This phenomenon occurs when an instrument makes contact with a certain tissue, this can be the patient's abdomen or some other body tissue. The 'Stick-Slip phenomenon' can play a role regarding tissue manipulation during MIS (Van Den Dobbelsteen, Schooleman, & Dankelman, 2007).

*Design Requirement 8. Fulcrum Effect

*Design Requirement 9. Stick-Slip phenomenon

Research by Gallagher et al. (2009) and Cushieri, Francis, Crosby and Hanna (2001) indicated the importance of developing / testing for psychomotor and dexterity skills among laparoscopy students during their training process. Dexterity includes spatial perception, coordination between hands and eyes*, the ability to aim, ambidexterity, steadiness of hands and arms* as well as cognitive and personality traits (Cusheieri et al. 2001). In addition to these abilities, it is important for students to develop visual – spatial perceptions that will enable them to perform diagnosis through images (Cuschieri et al. 2001). For this, the researcher considered the views of Anastakis et al. (2000) who said that laparoscopy training programs must facilitate visual recognition of objects that are projected in 2D / 3D space as well as 2D / 3D object rotations and translations. This includes the transfers of 3D objects into 2D pictures, which will enable students to translate body parts onto the screen for further analysis and diagnosis. Conversely, students must also be able to infer 3D orientations from 2D images projected onto a screen. This is to avoid loss of depth perceptions that typically occurs during laparoscopic surgeries when the area to be operated is obscured and viewable using only camera and screen (Arendt, 2017). Furthermore, students must also be able to guide their hand movements from the 3D / 2D imagery projected onto the display screens (Küpper, 2018).

*Design Requirement 10. Hand-Eye Coordination

*Design Requirement 11. Steadiness

Studies by Verwey (1996) established that when tasks are repetitive, there is the risk of motor sequence learning (MSL) occurring*. This is the automation of successive movements which is undesirable in situations of laparoscopy surgery where one must be able to dynamically adapt movements to the situation. This suggests that the design of the laparoscopy simulator must be configurable and flexible. Arendt (2017) pointed out the importance of being able to assess student performance and rate of acquisition of laparoscopic technical skills*. In a simulated training environment, evaluation of low-fidelity dexterity tasks provides an approximation of overall technical laparoscopic skills (Arendt, 2017). Such an evaluation mechanism for the outcomes of laparoscopic training are also simple, inexpensive and low-risk. Accordingly, the design of the simulator in this paper provided for the assessment of low-fidelity tasks.

*Design Requirement 12. Configurable and Flexible (against Motor Sequence Learning)

*Design Requirement 13. Assessment of Low Fidelity Task

Mandolfino et al. (2016) indicated that simulated laparoscopic training programs must be based on virtual reality which enable students to acquire manual skills associated with various laparoscopic surgical techniques. In addition, research by Yiannakopoulou et al. (2016), Andreatta et al. (2006), Lehman et al. (2012), Zendejas et al. (2013) and Mandolfino et al. (2016) indicated the need for cost-effective simulated laparoscopic training solutions.

Based on the above findings, the various requirements from a laparoscopic training simulator were summarized as indicated in Figure 3.

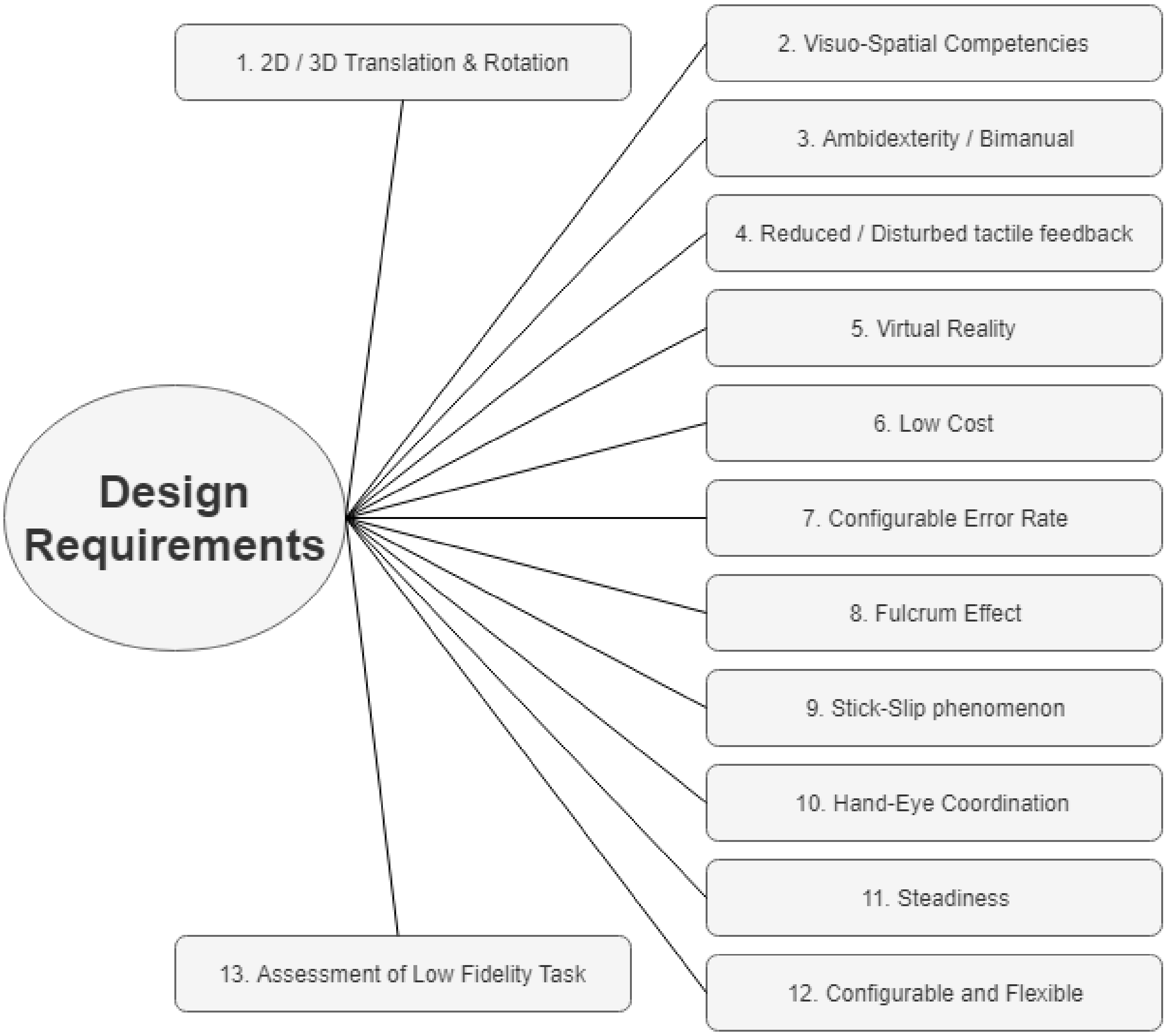

Figure 3. *Design requirements for a low-fi laparoscopy simulator for studying learning of complex motor skills.*

1.2.2. Design requirements prioritization

The objective of this research is to create a low-fi simulator to study learning of complex motor skills, therefore it is not be necessary / possible to create a design that meets all requirements to resemble a laparoscopy procedure. That is why a distinction has been made between 'Must' and 'Should' requirements. The unique contribution of this research is the design of an economical laparoscopy simulator, as simulation in laparoscopic training is an expensive proposition nowadays.

For this reason, the requirements are Low Cost and Assessable essential ‘Musts’. Learning laparoscopy through simulation is a viable alternative to other methods such as apprenticeships, so Virtual Reality also is an essential Must.

Because it is a low fidelity design, the requirements 2D / 3D translation and rotation, Reduced / Disturbed tactile feedback, Steadiness, Stick-Slip phenomenon and Fulcrum Effect are categorized as ‘should’, however in order to resemble a laparoscopy procedure, it is essential to include as many as possible of these requirements in the design. Essential to create a resembling complex motor task are Visuo-Spatiability, Bimanuality and Hand-Eye coordination. These aspects should be the essence of the complex motor task. To prevent Motor Sequence Learning from appearing, also Configurability and Flexibility is an indispensable requirement.

Table 1. *Magnitude Design Requirements*

Design Requirements	**Magnitude**
1. 2D / 3D Translation & Rotation	Should
2. Visuo-Spatial Competencies	Must
3. Ambidexterity / Bimanual	Must
4. Reduced / Disturbed tactile feedback	Should
5. Virtual Reality	Must
6. Low Cost	Must
7. Configurable Error Rate	Must
8. Fulcrum Effect	Should
9. Stick-Slip phenomenon	Should
10. Hand-Eye Coordination	Must
11. Steadiness	Should
12. Configurable and Flexible	Must
13. Assessment of Low Fidelity Task	Must

2. Simulator design

As stated, the goal of this paper is to develop a low-fi laparoscopy simulator that is economical and resembles an existing, leading high-fi laparoscopy simulator. The study by Kaschub (2016), which describes four different dexterity tasks, is used to choose a basic design principle. The most suitable design principle is derived by checking the tasks for the thirteen design requirements derived in Chapter 1. The most suitable principle is then adapted and configured into a low-fi simulator which meets as many as possible design requirements.

2.1. Comparison low-fidelity dexterity tasks

Kaschub (2016) concluded in his research that it is partly possible to make predictions about learning complex motor tasks, such as laparoscopy, using dexterity tasks. Kaschub (2016) used four types of dexterity tasks in his research, namely, the Duncan Loop task, the Origami task, the Buzz Wire task and the Drawing task. These tasks will be compared to select the most suitable task as the basic design principle. This comparison will consist of mapping and scoring the presence of the Design Requirements (Table 2).

The Duncan Loop task used in the study from Kaschub (2016) consisted of a white cord with closed ends. The participant was shown a finished knot (Figure 4.) before the trial, to give the participant an idea of the result, and during the trial an instruction on how to make the knot.

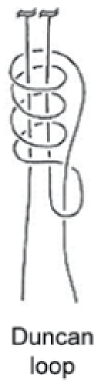

Figure 4. *Duncan Loop Instruction*

Note. Reprinted from *"Learning Complex Motor Procedures",* by Kaschub, V.L., 2016, *University of Twente*, p. 16.

The aim of the Origami task was for the participant to fold a Fox. This figure was chosen because it was at a basic folding level. The instruction consisted of eight pictures representing each one folding step (Figure 5.)

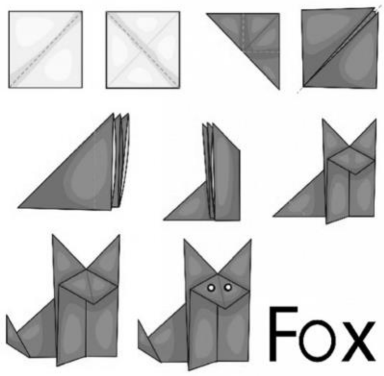

Figure 5. *Fox Origami instruction*

Note. Reprinted from *"Learning Complex Motor Procedures",* by Kaschub, V.L., 2016, *University of Twente*, p. 17.

The Buzz Wire was a task inspired from a childhood game with the intention of moving a ring from point A to point B without touching the wire. The wire was formed with different sized curves and also had two three-dimensional aspects. When the wire was touched a red LED light blinked to count the error. An example of a Buzz Wire task is depicted in Figure 6, this is not the Buzz Wire used by Kaschub (2016).

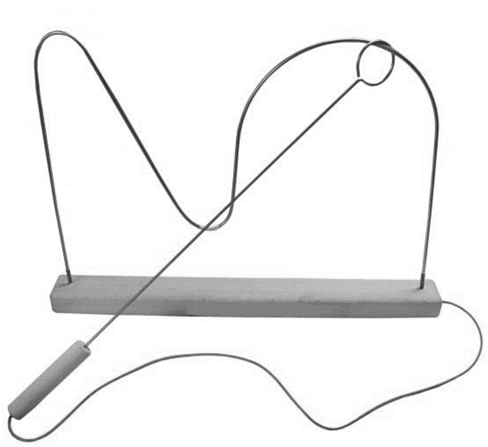

Figure 6. *Buzz Wire task (AVRON, n.d.)*

The goal of the Drawing task was to draw a figure according to the reflected image in a mirror. A cardboard box was used to hide the paper from the participant. The box had an opening and a mirror to see the mirrored figure (Figure 7).

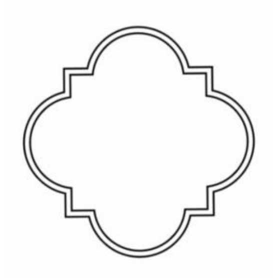

Figure 7. *Fill out Template for Drawing task*

Note. Reprinted from *"Learning Complex Motor Procedures",* by Kaschub, V.L., 2016, *University of Twente*, p. 18.

The EndoProto simulator created by Küpper (2018) who also used the paper of Kaschub (2016) is not included as an optional design because no 'learning' occurred. The participants did not improve their performance (time on task and error rate) during their sessions. Since the purpose of this research is to study the learning of complex motor tasks, using a low-fi simulator, this is not a valuable design for this study.

In addition to the comparison between the four dexterity tasks, the high-fi LapSim Simulator and a laparoscopy procedure are also included in the comparison. The LapSim is a virtual reality simulator used for training and as an assessment tool for laparoscopic procedures.

Table 2. *Mapping Design Requirements for dexterity tasks, LapSim Simulator and the Laparoscopy procedure*

	1	**2**	**3**	4	**5**	**6**	**7**	8	9	**10**	11	**12**	**13**	**TOT**(Must)
Duncan Loop Task		x	x		x	x				x			x	**6**(6)
Origami task		x	x		x	x				x			x	**5**(5)
Buzz Wire task		x		x	x	x	x			x	x		x	**8**(6)
Drawing task		x			x	x		x	x	x			x	**7**(4)
LapSim Simulator	x	x	x	x	x		x	x		x	x	x		**10**(5)
Laparoscopy procedure	x	x	x	x				x	x	x	x			**8**(3)

1. 2D / 3D Translation & Rotation
2. **Visuo-Spatial Competencies**
3. **Ambidexterity / Bimanual**
4. Reduced / Disturbed tactile feedback
5. **Virtual Reality**
6. **Low Cost**
7. **Configurable Error Rate**
8. Fulcrum Effect
9. Stick-Slip phenomenon
10. **Hand-Eye Coordination**
11. Steadiness
12. **Configurable and Flexible**
13. **Assessment of Low Fidelity Task**

** The bold design requirements are categorized as 'Must'.*

Based on the mapping of the design requirements, the Buzz Wire task is chosen as basic design principle, because it fulfills eight design requirements, six of which are categorizes as 'Must'. However, some design requirements, such as '3. Ambidexterity / Bimanual', have to be added to the simulator design to increase the resemblance with the LapSim Simulator to study learning of complex motor tasks.

2.2. Buzz Wire Simulator design

The Buzz Wire design by Kaschub (2016) was made out of wood, a handle and a metal wire with some variating curves. When the wire was touched with the ring a red lightbulb lighted up. This light was used to score the errors. However, it was difficult to score these errors in a precise manner, because the red light flickered too quickly, resulting in invalid measurements of the error score. Nevertheless, the learning curves of the Buzz Wire were stable and did not decrease as much as with the other dexterity tasks from Kaschub (2016). Difficulties in the used setup were; stiffness of the wire and the goal of the task. It was not clear to all participants where to focus, on speed or on accuracy. This resulted in different strategies. These difficulties can be taken into account in the design of the new simulator.

2.2.1. Prototype v1

For the current research a first prototype was designed. The goal was to make the task bimanual by attaching point B, the end, to another handle. In addition, the Fulcrum effect was added to the setup by creating an 'entrance point' for the right handle. Further, the new design also had to be configurable and flexible and the number of error rates should be manipulable. These changes were added in the first prototype (Figure 8.).

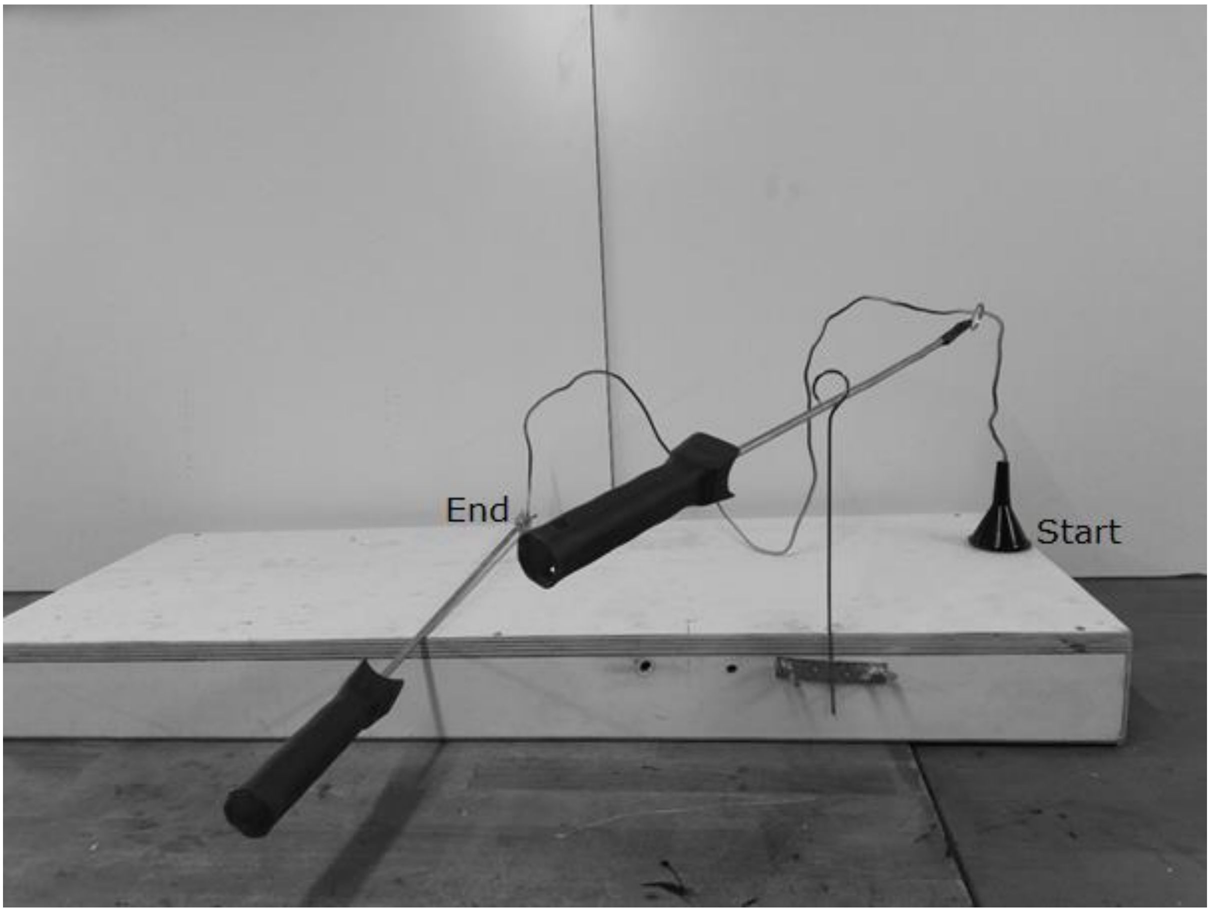

Figure 8. *Prototype v1; Buzz Wire Simulator*

2.2.1. Prototype v2

The first prototype fulfilled expectations, worked and showed no serious problems. The wire was highly configurable as was the ring. In addition, the Fulcrum effect was applied by adding the standard through which the first handle went. Further, the task became bimanual because both handles had an effect on the task. However, this entailed some problems. For example, there was too much freedom of movement with the second (left) handle. With this amount of freedom the wire could be straightened which, would have too much influence on the task. Two solutions were used in the second prototype (Figure 9.). The first adjustment was adding a second standard for the second handle. As a second option, the end of the second handle (wire end) its movement was limited by a thread that could be attached at various points on the box. In figure 9. the thread starts from the left handle (T0) to the first attachment point on the box (T1) which is behind the wire's origin (W0). In addition, the thread could also be attached to the center of the box for a different effect (T2). Each adjustment was tested extensively both individually and in combination with the other adjustments. Ultimately, a basic setup was chosen and the first design could be made. The decision was made to omit the thread and continue with two standards, resulting in a fulcrum effect for both hands. Also, the standards implement the Stick-Slip phenomenon. The handles don't slide smoothly through the standards which creates a similar, magnified, effect as in laparoscopy.

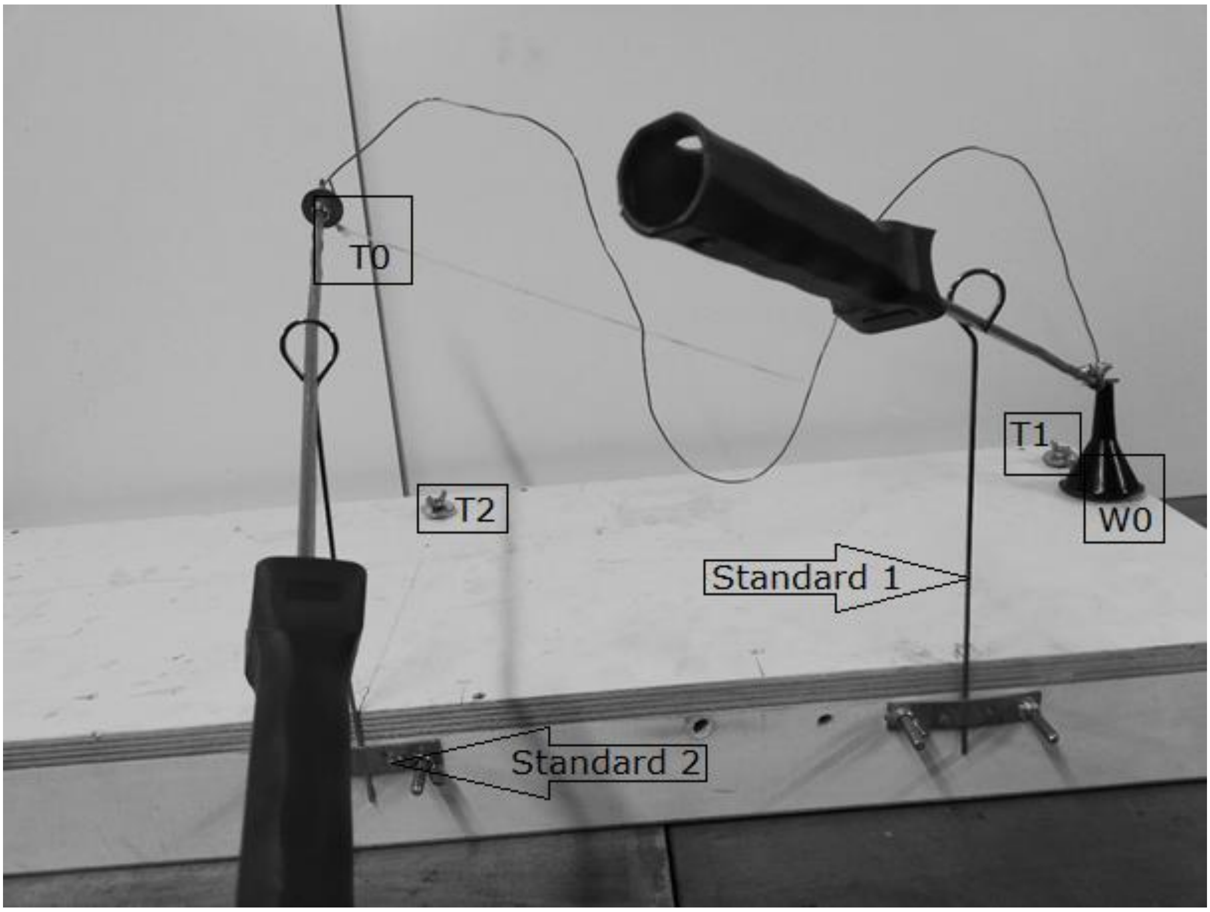

Figure 9. *Prototype v2; Buzz Wire Simulator (W0 = Wire Origin / start, T0 = Thread Start, T1= Thread attachment point 1 and T2 = thread attachment point 2.*

2.2.1. Buzz Wire Simulator

The prototypes led to the design of the Buzz Wire Simulator (Figure 10). As may be observed in figure 10, the underlying principle of the design used in the simulator was that of the 'Buzz Wire dexterity task'. The current design tests the participants learning of the complex motor skill resembling a laparoscopic procedure. A so-called 'Arduino' is built into the box. This is a kind of computer that processes the generated data and controls the LCD display, speaker and LEDs. The Buzz Wire Simulator can be started by connecting the power supply to the Arduino (connecting the included USB cable to the built-in socket at the left side of the box). Subsequently, both handles are operated simultaneously starting with the right handle from the contact point on the box and ending with the contact point that is connected to the left handle. While doing this, the participant makes a series of complex motor movements resembling a laparoscopic procedure. The trial time starts when the ring (first handle) no longer makes contact with the starting point (contact point on the box), and ends when the ring makes contact with the end point (contact point on the second handle). The green LED lightens to inform the participant the trial has been succeeded. The progress of the trial time is visible on the built-in LCD display. In this process of moving from start to finish, the student must not make any contact with the copper wire. Every contact is counted as an error. When an error occurs, both visual (red LED lightens) and auditory feedback (Buzz sound) is given. The student's performance is evaluated as a measure of time taken from start to finish and the number of errors generated. This evaluation is presented on the LCD display. All data is reset when the ring connects with the starting point (orange LED lightens). When this ring leaves the starting point again, the process repeats itself and starts a new trial.

As stated, an Arduino is being used for the controls, feedback and data collection. An Arduino includes a physical programmable circuit board and a piece of software. This software is open-source and can be used to write and upload computer code to the physical board. The environment is based on the C / C++ language. The main functions of the Arduino are; power supply, control over the LCD display, and collection and presentation of feedback (LEDs, buzzer, LCD display). During the programming of these functions, some issues occurred. The first issue which came up at an early stage of programming and testing was the contact checking interval. Every how many seconds should the program check all contacts? This is a new (unwanted) variable that affects the data, and in particular the data concerning errors which is a crucial part of the performance evaluation of the participant. The greater this interval, the greater the chance that an error will be missed. The smaller this interval, the more sensitive the program becomes (every vibration will be measured as a separate error). To determine a suitable interval some tests have been done, the results of these tests are shown in Appendix IV. After studying this data, it was decided to check the contacts every 20ms. This resulted in each vibration of the wire during one error (trembling contact) being counted as a new separate error. To still count the number of errors realistically, a new variable has been added to the program; 'errorInterval'. The number of this variable is the number of milliseconds that an interval between an error check lasts. Because the duration of an error is also measured, this variable is therefore the minimum duration of an error. After some more testing, see Appendix IV, it was decided to let this interval last 200 milliseconds. Each error therefore lasts at least 200 milliseconds. The duration of an error also raised another issue. This third issue related to the possibility of ‘cheating’. With the presence of only the first two initial data output variables (trial time and errors) it was possible to make a one-time contact with the wire, a first error, and then maneuver all over the wire towards the end, without losing contact. In this way a very fast time is set with only one error. To make this phenomenon visible, a third data output variable has been added; Error Percentage. This variable measures the error time (the duration of an error) and compares this time with the total trial time. With a percentage as output. The code of the final program is attached in Appendix III.

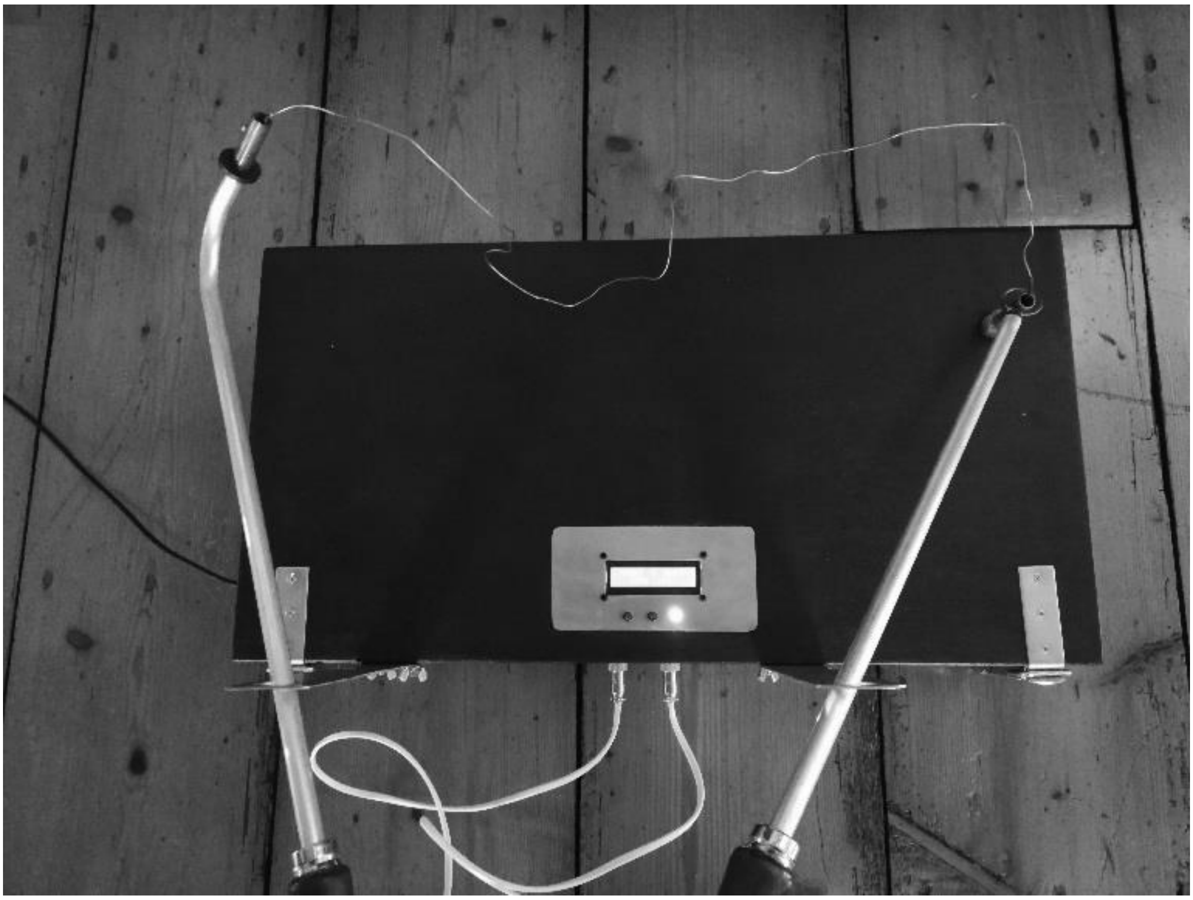

Figure 10. *Design v1; Buzz Wire Simulator*

2.3. Analysis Design Requirements & Resemblance Spectrum

In the Buzz Wire Simulator design, most of the design requirements are met (table 3). The requirement to operate both handles simultaneously tests for ambidexterity, spatial competencies and hand-eye co-ordination. The free nature of the movements required to practice on the simulator avoids motor sequence learning. The simulator evaluates error rate and performance time of low-fidelity tasks. The movements required to operate the handle resemble those required in laparoscopic procedures. It is a form of virtual reality as the student practices on a model that mimics real life operations. Since the handles pass through stainless steel holes that approximate laparoscopic devices that pass through abdominal walls, the simulator facilitates testing of the fulcrum effect. Furthermore, the simulator was developed at very low costs, thereby fulfilling the criteria that simulators for laparoscopy training must be cost-effective. The only design requirement not incorporated into this simulator is the translation of camera perceptions into hand movements. A schematic overview of the design requirements which are met in the Buzz Wire Simulator can be found in Table 3.

Table 3. *Mapping Design Requirements for dexterity tasks, LapSim Simulator and the Laparoscopy procedure*

	1	**2**	**3**	4	**5**	**6**	**7**	8	9	**10**	11	**12**	**13**	**TOT**(Must)
Duncan Loop Task		x	x		x	x				x			x	**6**(6)
Origami task		x	x		x	x				x			x	**5**(5)
Buzz Wire task		x		x	x	x				x	x		x	**7**(5)
Drawing task		x			x	x		x	x	x			x	**6**(4)
Buzz Wire Simulator		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**12**(8)
LapSim Simulator	x	x	x	x	x		x	x		x	x	x		**10**(5)
Laparoscopy procedure	x	x	x	x				x	x	x	x			**8**(3)

1. 2D / 3D Translation & Rotation
2. **Visuo-Spatial Competencies**
3. **Ambidexterity / Bimanual**
4. Reduced / Disturbed tactile feedback
5. **Virtual Reality**
6. **Low Cost**
7. **Configurable Error Rate**
8. Fulcrum Effect
9. Stick-Slip phenomenon
10. **Hand-Eye Coordination**
11. Steadiness
12. **Configurable and Flexible**
13. **Assessment of Low Fidelity Task**

** The bold design requirements are categorized as 'Must'.*

By adjusting and configuring the dexterity task, there is a difference in resemblance between the Buzz Wire Simulator and the Buzz wire task from Kaschub (2016). To show the level of resemblance schematically Arendt (2017) created the so called ‘Resemblance Spectrum’. The idea of this concept is that all designs and tests only vary in resemblance of laparoscopy in the operating room. Arendt (2017) expects that the failure of tests and designs in predicting laparoscopic performance is due to the degree of resemblance. The tests do not cover the combination of manual dexterity and cognitive demand which is involved in actual laparoscopy procedures. The spectrum has low-fidelity techniques such as dexterity tasks on the one end and runs to high-fidelity techniques such as procedures in the LapSim Simulator on the other end, with the actual laparoscopy procedure on the far-right end. According to Arendt (2017), the spectrum provides a basis for investigating how resembling tests and designs are and should be. The study by Arendt (2017) has shown that simple dexterity tasks are not resembling enough to make systematic and controlled statements about the learning curve of laparoscopy students. This study continues the search for a resembling low-fi research tool. Figure 11 is a modified depiction of the location of the Buzz wire Simulator in the Resemblance spectrum by Arendt (2017).

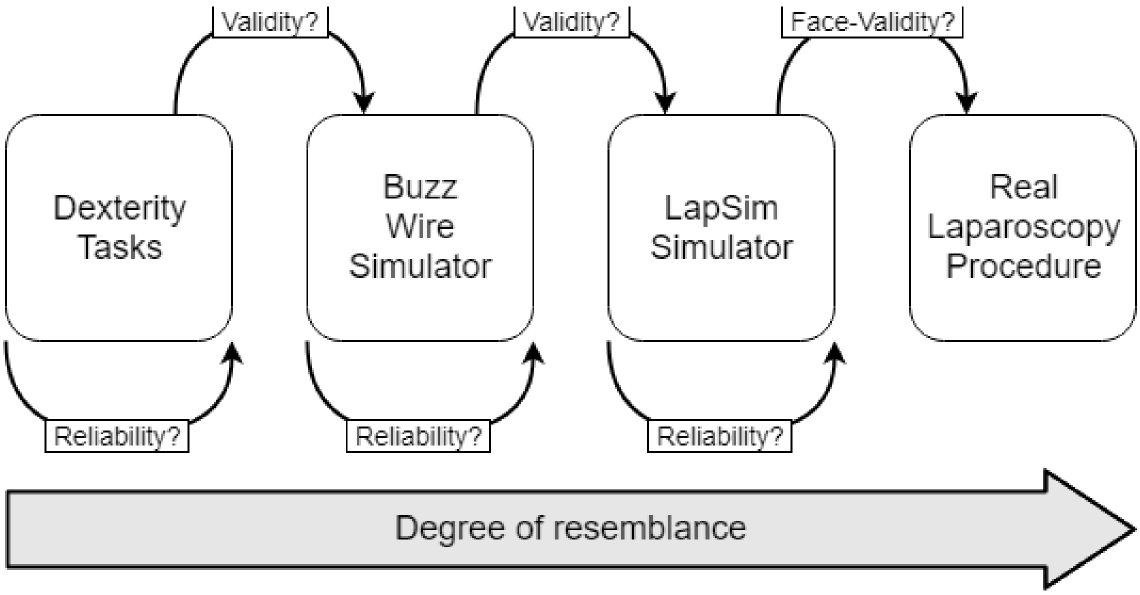

Figure 11. The resemblance spectrum. The x-axis depicts the degree of resemblance, ascending from left to right. The arrows appoint the relationships between the test suites.

Note. Own design, based on: *“Towards reliable and valid prediction of MIS-performance with basic laparoscopic tasks in the LapSim and low-fi dexterity tasks”,* by Arendt, A., 2017, *University of Twente*, p. 13.

3. Design evaluation

This chapter evaluates the Buzz Wire Simulator design. To gain insight into the performance and the functioning of the Buzz Wire Simulator, a validation research has been conducted. Firstly, the method of the validation research is briefly described. The method provides information about the goal, participants, used materials, procedure, design, measurements and the data analysis. Subsequently, the results and the conclusions of the validation study are being described.

3.1. Validation research

The Weimer (2019) study is used to validate the Buzz Wire Simulator. Weimer (2019) explored the effects of time pressure on learning laparoscopic skills using the LapSim Simulator. A reproduction of this study using the Buzz Wire Simulator offers the possibility to make a comparison between the renowned LapSim Simulator and the Buzz Wire Simulator.

3.1.1. Goal

The first and main goal of this validating research is to evaluate the functioning of the Buzz wire Simulator. The second goal is to validate the Buzz Wire Simulator design by exploring the similarity and resemblance in comparison to the LapSim Simulator. The research methods and results of Weimer (2019), who used the LapSim Simulator to explore the effect of time pressure on the performance of novices in MIS practice tasks, will be used for this validation. Weimer (2019) states that the effect of time pressure on learning curves of novices in MIS procedures is still unclear. The goal of the Weimer (2019) study was to test the hypothesis; Novices who experience time pressure are improving faster than novices who are not experiencing time pressure. Testing this hypothesis is not a goal of this current study. This study will compare the results on the LapSim Simulator with the results on the Buzz Wire Simulator to gain insight into the differences and similarities of these results.

This comparison will provide insight into the capability of the Buzz Wire Simulator to do research into individual learning curves. It will therefore be examined whether learning occurs among the participants of the Buzz Wire Simulator study. In addition, the design as a whole will be evaluated, for example for research usability and adaptability will be evaluated.

3.1.2. Participants

A convenience sample of 18 participants participated in this study. All participants were between the age of 21 and 27, with a mean age of 25. Of the 18 participants 13 (72%) were male and 5 (28%) were female. Participants with physical limitations related to hands and coordination, which influenced the operation of the Buzz Wire Simulator, were excluded from participation

3.1.3. Method

Buzz Wire Simulator. Each participant has been working on the low-fi Buzz Wire Simulator created in this study. The current design (Figure 10) tests the participants learning of the complex motor skill resembling a laparoscopic procedure. The underlying principle of the design used is that of a 'Buzz Wire' which tests the participant's performance. In short; the participant makes a series of movements related to laparoscopic procedures using the two handles. Both handles are operated simultaneously starting with the right handle from the contact point on the box and ending at the contact point that is connected to the left handle. In this process of moving from start to finish, the student must not make any contact with the copper wire. The participant's performance is evaluated as a measure of time taken from start to finish for each trial and the amount of errors generated.

Score form. A score form was used to systematically collect the results. For each trial the: time on trial, amount of errors, error percentage and mental demand (scale 1-10) was noted. In addition, there was room to take notes per phase. An example of the used score form is attached in Appendix II.

Procedure. The design used was a 'within-subject design'. First of all, the participant was orally introduced to the validating study. The instructions were the same for each participant. Thereafter, the operating and functioning of the Buzz Wire Simulator was explained. Subsequently, the opportunity was offered for the participant to ask questions. If this was not the case, or if the questions were answered, the first trial was started. Every participant was supposed to complete 20 trials on the Buzz Wire Simulator; for every trial, a single simulator setup was used. The shape of the wire in this setup is shown in Figure 12. Each participant was asked to complete the trial as fast and as accurate as possible. Four variables were noted on the score form after each trial: Time on trial, Errors, Error Percentage and Mental Demand. The Arduino in the Buzz Wire Simulator gave, via the LCD display, at the end of each trial: the duration of the trial, sum of the errors of the trial and calculation of the error percentage of the trial. In addition, at the end of each trial the participant was asked: “How mentally demanding was this trial? (on a scale from 1-10, where 1 = lowest and 10 = highest)”. Once this was noted, the next trial could be started.

The maximum performance of the participant was calculated on basis of the first 10 trials. Time pressure was added for trials 11-15. The participants had to do these ‘time pressure trials’ 20% faster than their time on trial number 10. The aspired maximum duration for trials 11-15 was announced after trial 10. The duration of a trial could be monitored during this trial via the LCD display. Lastly the participant executed trials 16-20, where the time pressure was omitted. In the study by Weimer (2019) the maximum performance of the trials 1-10 was compared to the performance of the last 5 trials (16-20) to explore if the ‘time pressure trials’ 11-15 had an effect on the maximum performance. This current study explored the similarities and differences between the results of this research and the research of Weimer (2019)

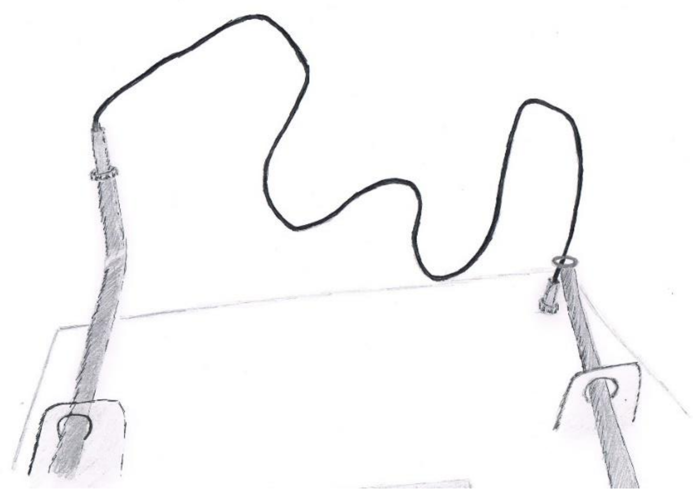

Figure 12. *Wire shape, Buzz Wire Simulator*

Measurements. Four variables were noted during this study. Three of them were tracked by the Arduino in the Buzz Wire Simulator, the fourth variable was obtained by asking a question. Table 4 provides a schematically overview of the four variables.

Table 4. *Measurements validation study; Buzz Wire Simulator*

	Measurement
ToT (Time on Trial)	Trial time, the time it took the participant to get from the starting point to the end point with the ring. Displayed on the LCD display at the end of every trial.
Errors	The number of contacts with the wire during the trial. Summed by the Arduino and displayed on the LCD display at the end of each trial.
Error Percentage	The percentage of the trial time that the ring was in contact with the wire. Calculated by the Arduino and displayed on the LCD display at the end of each trial.
Mental Demand	The answer given by the participant to the question: "How mentally demanding was this trial? (on a scale from 1-10, where 1 = lowest and 10 = highest)".

3.1.4. Data Analysis

The same data analysis was used as in the Weimer (2019) study; the reparametrized Learning Curve Model. This is a non-linear effects model which uses an exponential learning curve as a likelihood function. This function, called ERY, constructed the individual learning curves. The learning curves were represented using the following formula:

$$Y_{ptN} = Asym_{pt}(1 + \exp\left(-Rate_{pt}\left(N + Prev_{pt}\right)\right))$$

Note. Reprinted from "*Towards an effective MIS simulator-based training with basic laparoscopic tasks: The impact of time pressure on the learning process*", by Weimer, C.O.H., 2019, *University of Twente*, p. 16.

Three learning curves were constructed for each participant. Each learning curve reflects one of the three phases (Trial 1-10, 11-15 and 16-20). These curves were based on TOT (Time on Trial) and Errors and contained the parameters: Asymptote, Rate and Previous Experience.

3.2. Results and conclusion validation research

This paragraph provides the data output of this validation results. The results shown are shown briefly. When observing and interpreting the correlations, asymptotes, data and plotted curves, it must be noted that only 18 participants only performed 20 trials (10, 5 and 5).

3.2.1. Correlations

Figure 13 shows the correlation between Demand and Damage (errors) which is -0.183, the correlation between Demand and ToT (Time on Trial) which is 0.327 and the correlation between ToT and Damage (Errors) which is 0.065.

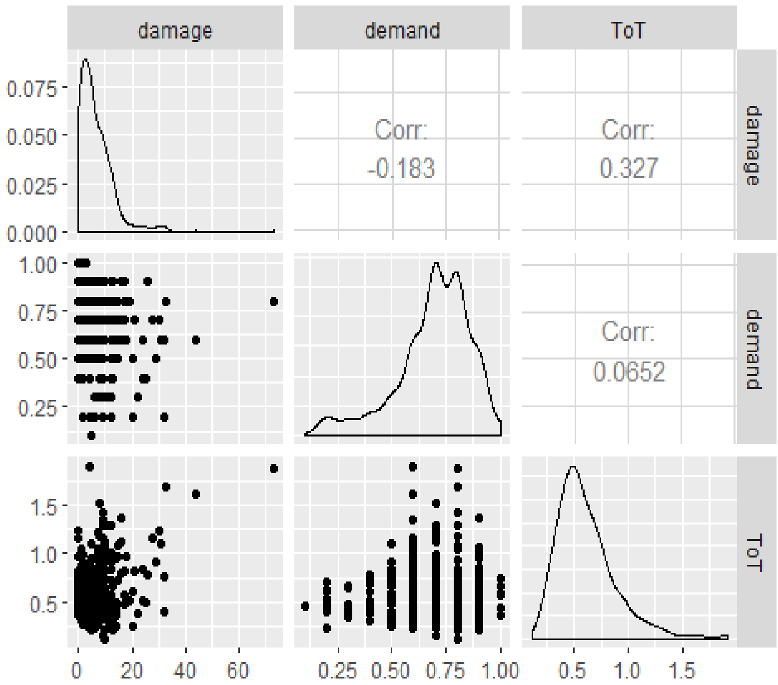

Figure 13. *Correlations; Damage (Errors), Demand and ToT (Time on Trial)*

3.2.2. Comparing asymptotes

Table 5 shows the result of asymptote estimation. Note that: the asym Intercept is the (reference) asymptote in the first phase. Asym Phase2_pressure and Phase3_free are *not* the differences to the reference asymptote (Intercept), but *proportions*. E.g. ToT Phase2_pressure asymptote is about 60% of first phase (Intercept).

Table 5. *Comparing asymptotes; results Buzz Wire Simulator*

Model	**Fixef**	**Center**	**Lower**	**Upper**
Damage	Intercept	5.63	3.62	8.44
Damage	Phase2_pressure	0.71	0.53	0.94
Damage	Phase3_free	0.55	0.37	0.76
ToT	Intercept	38.83	33.15	46.46
ToT	Phase2_pressure	0.59	0.54	0.64
ToT	Phase3_free	0.81	0.73	0.88

- *asym* Intercept is the (reference) asymptote in the first phase
- asym Phase2 and Phase3 are *not* the differences to the reference asymptote 1_free, but *proportions*, e.g. pressure phase ToT asymptote is about 60% of first phase.

3.2.3. Observed data

Figure 14 schematically displays an example of the observed data. The data of all participants can be found in the appendix I(a).

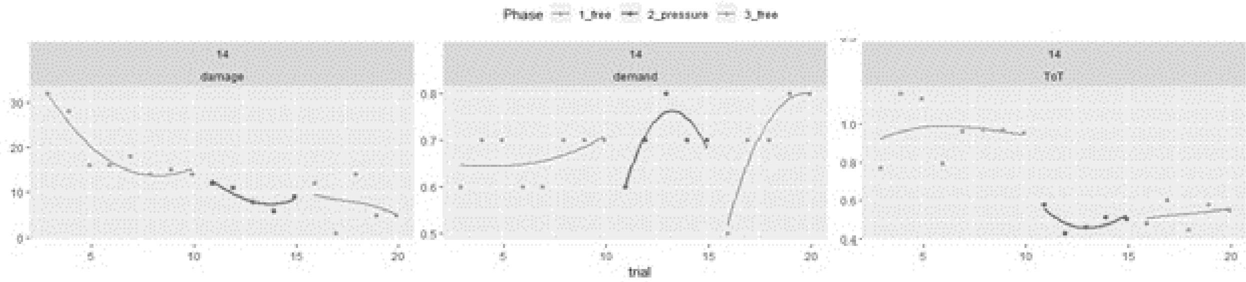

Figure 14. *Observed data example (participant 14); Damage (Errors), Demand and ToT (Time on Trial)*

3.2.4. Multilevel non-linear regression

Figure 15 schematically displays an example of the predicted learning curves. The predicted learning curves all participants can be found in the appendix I(b). These predicted learning curves are a result of multilevel non-linear regression analysis. Models are built for the variables: Damage (Errors) and ToT (Time on Trial). Here we compile the model using the formulas stated next to each variable:

Tot: ## perf ~ exp(-exp(rate) * (trial + pexp)) + exp(asym)

<environment: namespace:asymptote>

Using the compiled model above, an estimation has been made.

Damage: ## damage ~ exp(-exp(rate) * (trial + pexp)) + exp(asym)

<environment: namespace:asymptote>

Using the compiled model above, an estimation has been made.

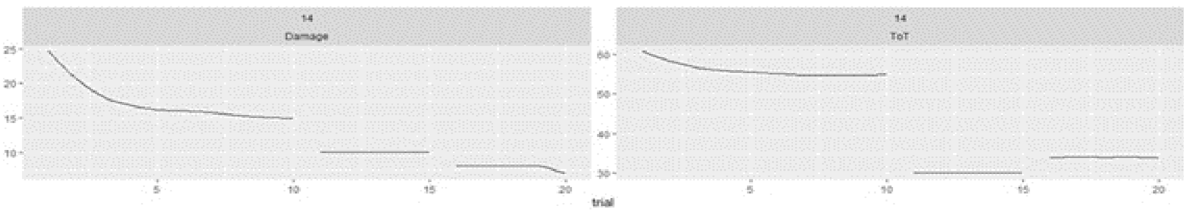

Figure 15. *Predicted learning curves example (participant 14); for Damage (Errors) and Tot (Time on Trial)*

3.2.5. Conclusion

As the title; ‘Designing a low-fi laparoscopy simulator for studying learning of complex motor skills’ indicates, a low-fi simulator has been designed. Design requirements have been established prior to designing the real simulator. An essential factor of a low-fi simulator are the costs of the final design. The Buzz Wire Simulator was finally constructed for a total amount of € 120. All essential design requirements are implemented successfully, in an economical way, in the Buzz Wire Simulator.

The next step, after creating the Buzz Wire Simulator, was to validate the new design. The goal was to evaluate the design by exploring the similarity and resemblance in comparison with the widely used LapSim Simulator. The research of Weimer (2019) has been used as a reference. Weimer (2019) used the LapSim Simulator to explore the effect of time pressure on the performance of novices in MIS practice tasks will be used for this validation. This current research examines the question; To what extend are the results on the Buzz Wire Simulator similar to the results of the LapSim Simulator?

First of all, the results (Figure 14, 15 and Appendix I) show that the respondents learn with the Buzz Wire Simulator. The fact that learning occurs, raises the opportunity to explore individual learning curves using the Buzz Wire Simulator. After comparing the results described in chapter 4 with the results of Weimer (2019) it can be concluded that learning on the Buzz Wire Simulator is, to some extent, comparable with the LapSim Simulator. Especially the behavior regarding Time on Trial is similar, the influence of time pressure on the trial time is also comparable. These results state that the Buzz Wire Simulator resembles the LapSim Simulator to some extent. It can be concluded that the Buzz Wire Simulator can be used for research into learning curves concerning complex motor tasks (Laparoscopy).

However, further research needs to be done with the Buzz Wire Simulator before it can be used instead of the more expensive LapSim Simulator regarding research on learning curves. For example, the results of the variable Errors are not entirely similar. This does not mean that the Buzz Wire Simulator is not resembling with the LapSim Simulator regarding this variable. Errors on the Buzz Wire Simulator are more complex than it appears at first glance. There is still much room for refining when it comes to making errors, this is elaborated in chapter 4.

4. Design criticism

This chapter provides design criticism and recommendations based on the results and experiences of the evaluation and validation research. In addition, detailed information will be provided about the functioning of the Buzz Wire Simulator.

4.1. General remarks validation study and data collection

This paragraph describes the general remarks and observations about the functioning of the Buzz Wire Simulator during the validation study.

4.1.1. What is the effect of the trial length?

First of all, is it the case that the longer a trial lasts, the more time the respondent has to make mistakes? Observing, this sometimes suggested that the longer the trial seemed to last, the more errors were seemingly made. It may be the case that the making of an error has an effect on the duration of a trail. It is also possible that the lack of a so-called 'flow' causes more errors and has a negative influence on the trial duration. It is conceivable that fluent movements are more effective to ‘make way’. A fluent motion pattern may not be exclusive to the Buzz Wire Simulator, but may also be present in other laparoscopy simulators (including the LapSim Simulator). ‘Making way’, cover a distance, is also applicable in these cases.

4.1.2. Do participants switch strategy, and what are the effects of these focus shifts?

It stood out that some respondents switched their focus, switching between focus on time on trial and errors. In this setting, this has a noticeable result on the learning curve or the possible lack thereof. It seems to be hard to be accurate and fast at the same time. Switching focus was sometimes caused by a lack of motivation and / or concentration. The concentration of respondents was not the same for everyone. Some respondents found it difficult to remain motivated during the trials. Especially during the first 10 repetitions and the last repetitions respondents declared to have difficulties regarding concentration and motivation. This variation in observable concentration had various causes. As mentioned, some people switched their focus, where others became irritated or nonchalant. Possibly seeing the results of the previous trial (Time on Trial and Errors) had an influence on the motivation / concentration / focus. For a few respondents, adding time pressure was a welcome challenge that motivated the respondents to once again concentrate on their task. It is therefore a necessity to keep the participant motivated and to stimulate concentration. This should be taken into account in future research. In addition, the strategy of the participant must be directed as much as possible, this can improve the reliability and validity of the investigation.

4.1.3. Are there different types of errors? (Sliding vs Tapping)

The nature of the errors varied remarkably between the respondents. Some respondents came to a halt in their movement towards the end when tapping the wire (Error). Their flow was therefore interrupted when an error occurred. The occurrence of an error often had a negative effect on the time on trial. With 'flow' is meant that there is a fluent movement pattern. This fluent movement pattern, flow, seemed the ideal approach during the validation study. Other respondents did not interrupt their flow in the event of an error and made a sliding motion with the ring along the wire. As a result, an error lasted slightly longer, but the flow was not interrupted. However, a few respondents were rushing resulting in exceptionally high error percentages. That states that they made an exaggerated sliding motion in the event of an error, and were therefore very fast (ToT), but kept in contact with the wire for a longer time during the trial.

4.1.4. What is the effect of stress? (recovery time)

Another notable consequence of an error was stress. The degree of stress in the event of an error varied considerably between respondents. In some cases, respondents gave up hope for that current trial when an error occurred. They bungled that trial. An error therefore regularly had profound consequences for the further course of the trial. Some respondents indicated to be annoyed by the buzzer. This irritation was often caused by making an error. A negative stimulus, such as stress and / or irritation, was conditioned on the buzzer sound. This sound was subsequently experienced as disturbing. However, in the end most participants indicated that they experienced the task as fun and exciting. There seemed to be a recovery time. Some participants who experienced stress as a result of, for example, an error got distracted and unconcentrated, they needed time to regain their focus. This recovery time might affect the learning curve of the participant.

4.1.5 Differences in bimanuality.

During the validation research a difference in bimanuality between the participants was visible. Some respondents often limited themselves to just moving the right hand (Ring). Others used both hands, effectively or not. The cause of these different strategies was unclear. The effect of phenomenon on the learning curve was also unclear. It might be the case that a full bimanual approach is more difficult to learn. The extend of bimanuality was a remarkable difference between the respondents and seemed to affect the time on trial and the making of errors. However, the effect was not clearly positive or negative. Some participants seemed to take advantage of a major bimanual approach, where this seemed too difficult for other participants. Caution might also influence bimanuality. If a participant is extremely careful, then the respondent seems inclined to move hands separately. One hand was often fixed to create a stable basis for the other hand. The coercion for bimanuality can be controlled with the shape and length of the thread.

4.1.6. Depth perception

Some respondents indicated that they had difficulty distinguishing depth during the experiment. Seeing depth or not makes the assignment much easier or more difficult. This does not affect individual learning curves because respondents are not compared. However, the task of the Buzz Wire Simulator may be too difficult or frustrating for the participant and in this way affect the learning curve or explain the absence of a learning curve at all. The view and depth perception of the respondents must therefore be taken into account. It is advisable to map the ability to distinguish depth and the sight of the participant prior to the Buzz Wire Simulator trails.

4.1.7. Time pressure

Lastly, the effects of adding time pressure and subsequently removing it had various consequences. In some phases the starting level seemed too high to show a learning curve in so few trials. To explain the effects of adding and subsequently omitting time pressure, and the possibility of the Buzz Wire Simulator to do research on this phenomenon, further research must take place. The research results look promising, but wider deployment and more intensive use of the Buzz Wire Simulator will have to confirm these results.

4.2. Functioning and recommendations Buzz Wire Simulator

This paragraph discusses the functioning of the design and provides recommendations for future research with the Buzz Wire Simulator.

4.2.1. Functioning

During the research, the Buzz Wire Simulator had no malfunctions in the software nor the hardware. The external of the simulator is quite robust. The built-in USB port is also not susceptible to interference and is sturdy. The LCD display and the levers with associated wires are to some extend tough and resilient. However, there is a sensitive network of wires on the inside of the simulator. The connections on the Arduino are also sensitive and can become loose. This must be handled with care. Despite the sensitive interior, it is possible to store the USB cable and the levers including wires in the simulator so that the device can be stored easily. With future adjustments, the wires can perhaps be protected better and more safely by, for example, the installation of cable ducts. These ducts can be installed fairly easily. They are inexpensive and therefore have nearly no influence on the costs of the simulator.

4.2.2. Recommendations

A point of attention was the configuration of the wire. This configuration was set up for each participant as shown in Figure 12. However, research has only been done with a one-sided configuration, there is therefore no insight into various configuration options. The shape of the wire must be taken into account for future use of the Buzz Wire Simulator. The shape and length influence the content of the trial and determine the difficulty level. The Buzz Wire Simulator comes with multiple copper wires (different thicknesses and therefore stiffness).

Another recommendation is to discover the in 4.1.1. is described fluent motion pattern. This a possible effective strategy when handling the Buzz Wire Simulator. With the use of a fluent movement pattern, the trial will probably take less time. The longer a trial, the more time there is to make errors. A research setup can be created where this phenomenon can be further investigated, with the goal to explore the effect and if there is a correlation with laparoscopy. A possible setup to study the fluent movement is to use different wire lengths and / or to forbid the participant to stop moving the ring (obligatory movement).

During the research it appeared that some participants seemed to benefit from a state of relaxation. Stress seemed to have an opposite effect and influenced the results negatively (4.1.4.). It is advisable to take stress into account for future use of the Buzz Wire Simulator. Concrete recommendation examples are, warning for errors (sound and light) and putting errors into perspective. Stress may affect the learning curve of the participants. Stress is not an exclusive issue with the Buzz Wire Simulator. Stress can also have major effect during a laparoscopy procedure. Interesting and useful follow-up research could be to investigate to what extent the effects of stress on the Buzz Wire Simulator match the effects of stress in Laparoscopy procedures or during acting on, for example, the LapSim Simulator.

Also important is being aware and taking into account the error percentage variable (Measurements 3.1.3.). The percentage of the trial time that the ring was in contact with the wire provides understanding of the nature of the error. The Arduino calculates and displays this variable on the LCD display at the end of each trial. In addition, clear instruction can stimulate a unilateral nature of errors. Further possible interesting follow-up research regarding errors is exploring of the effects of an error on learning. An error may cause stress, recovery time might be a characteristic variable.

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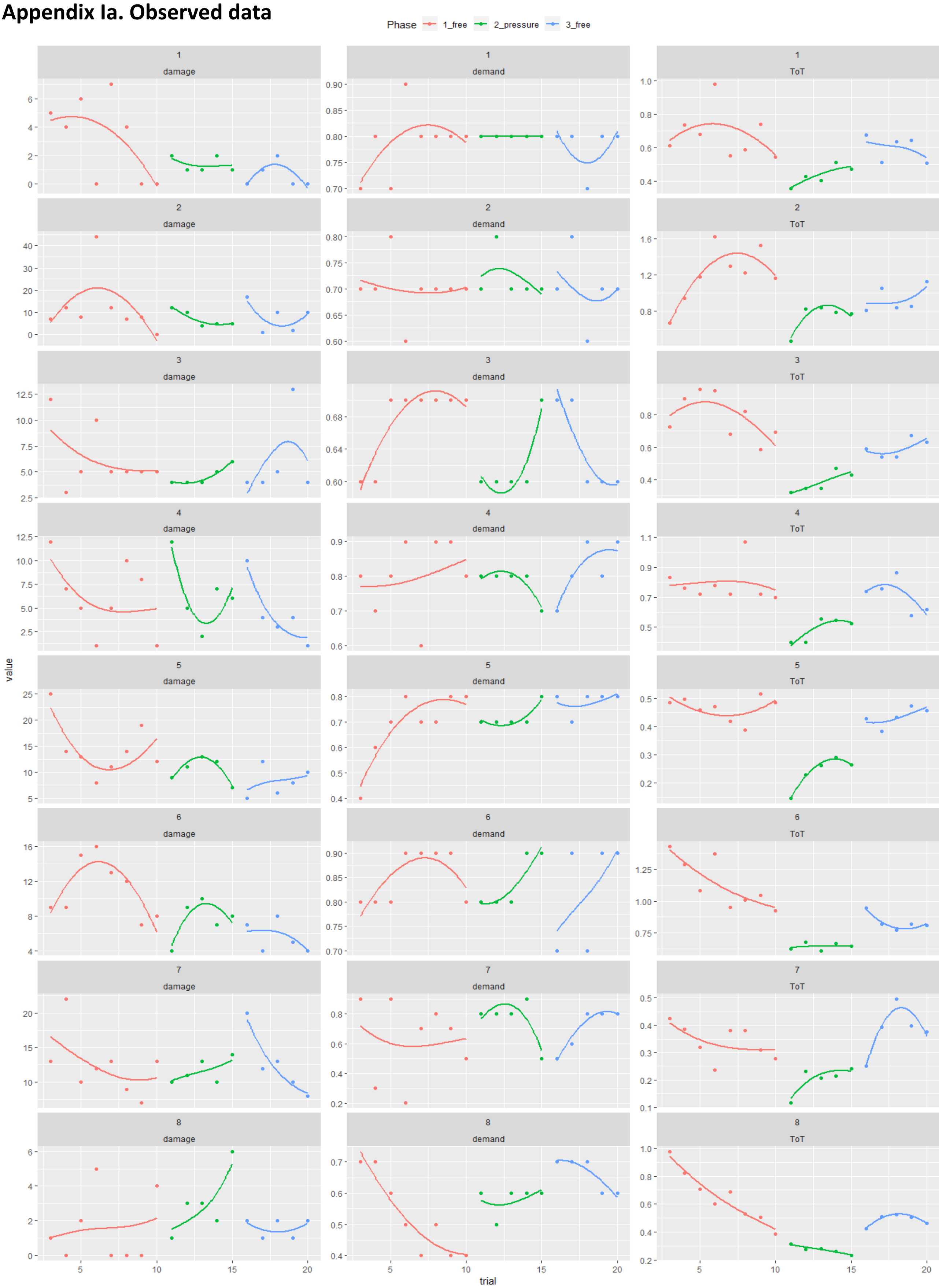
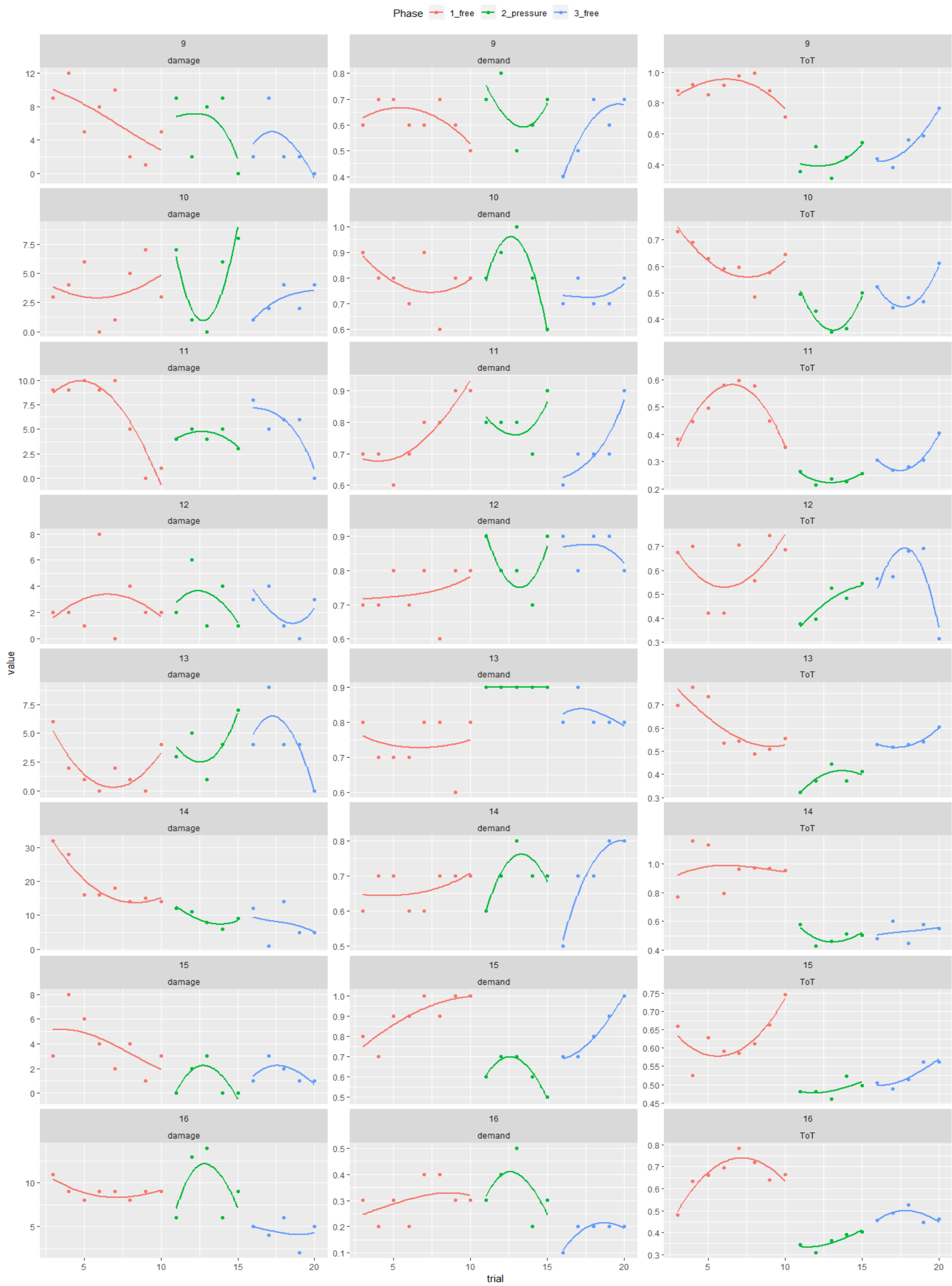
Appendix I. Validation study data

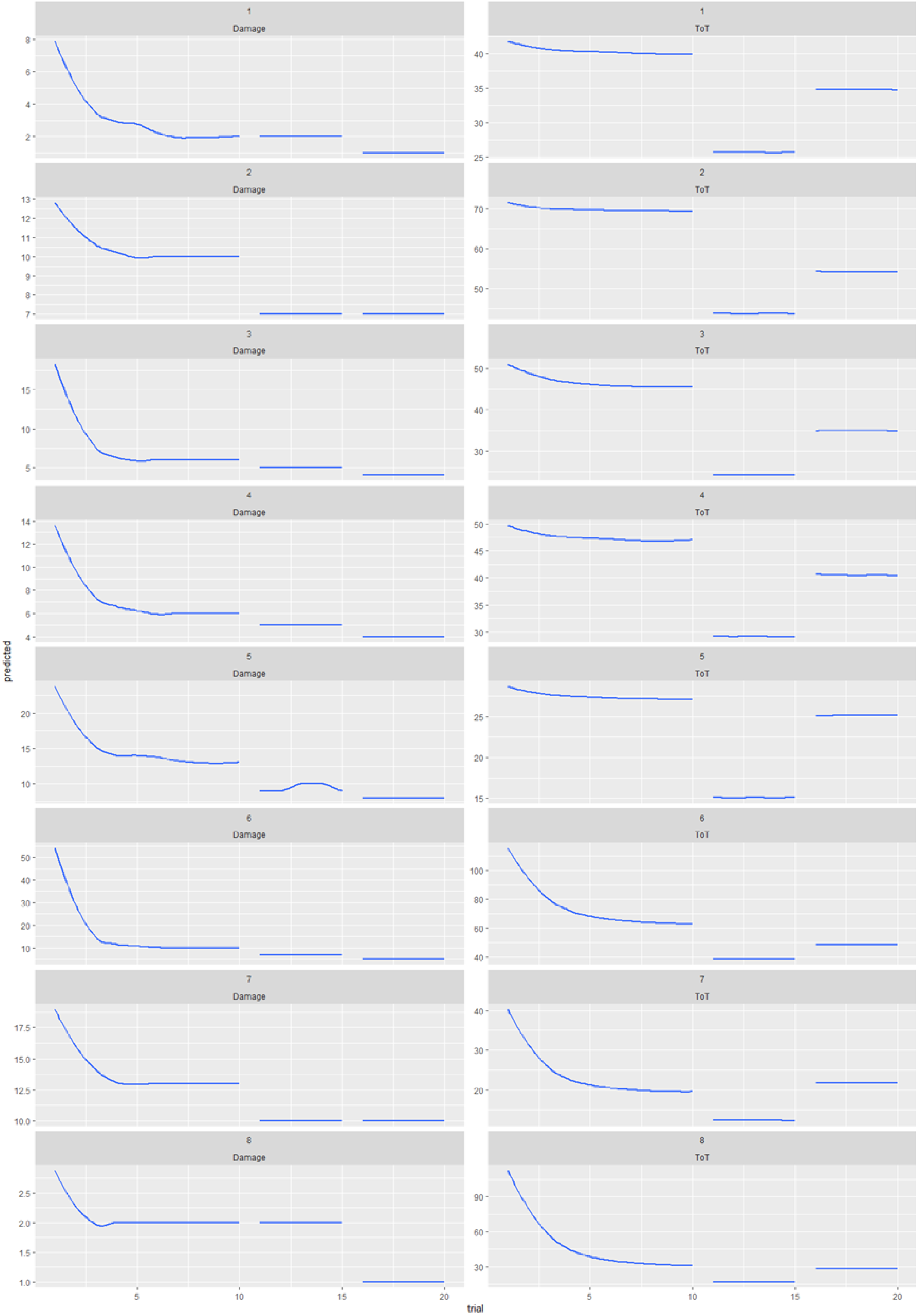
Appendix Ia. Observed data

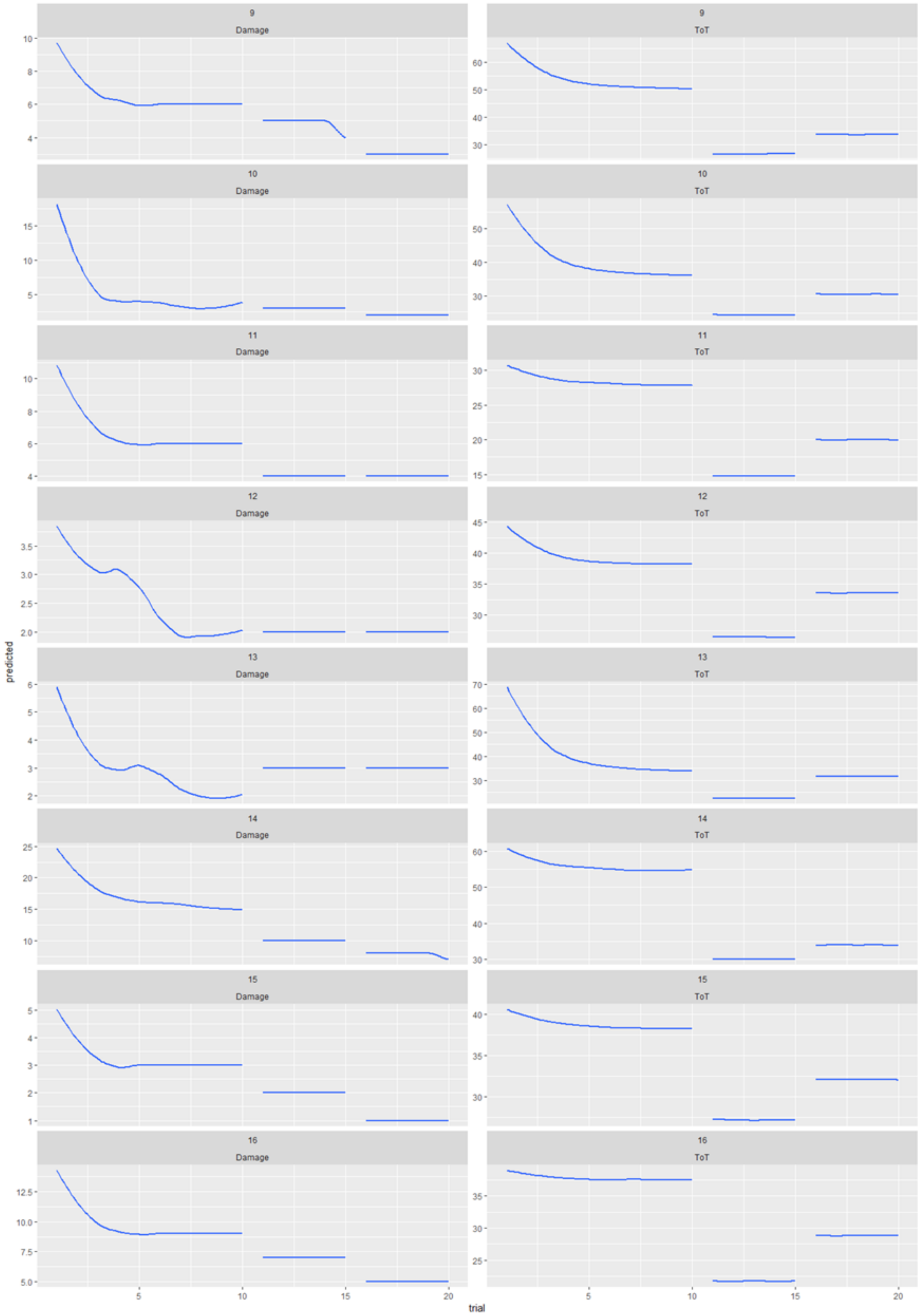




Observed data; Damage (Errors), Demand and ToT (Time on Trial)

Appendix Ib. Predicted learning curves (multilevel non-linear regression)





Predicted learning curves; for Damage (Errors) and Tot (Time on Trial)

Appendix Ic. Results Individual Learning Curves (Weimer, 2019, p19-21).

Individual learning curves

This analysis was conducted, in order to answer the research question on the influence of time pressure on the parameter maximum performance on an individual-level. Since the population-level effects cannot be generalized to every participant, an individual-level analysis was applied. Differences in the maximum performance could show different types of responses to time pressure and make it possible to come up with meaningful statements about the speed-accuracy trade-off.

On first sight, all the learning curves for the outcome variable time on task of both tasks seem to show the same pattern. Based on visual inspection, the learning curve of each participant shows a significant decrease in time on task when confronted with time pressure, and no change in time on task after the time pressure episode (figure 6). Four exceptions were found, which displayed no decrease or even a slight increase of time on task when starting the second phase of time pressure (figure 7).

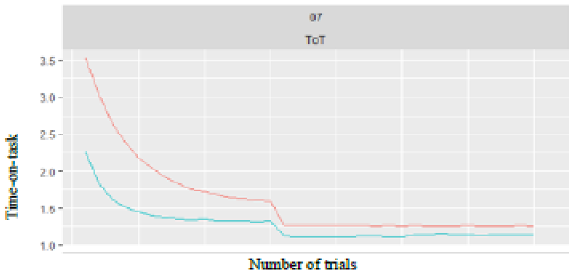


Figure 6. The usual course of a learning curve on individual-level, which displays the outcome variable time on task. The blue line displays the Lifting and Grasping task and the red line the Cutting task.

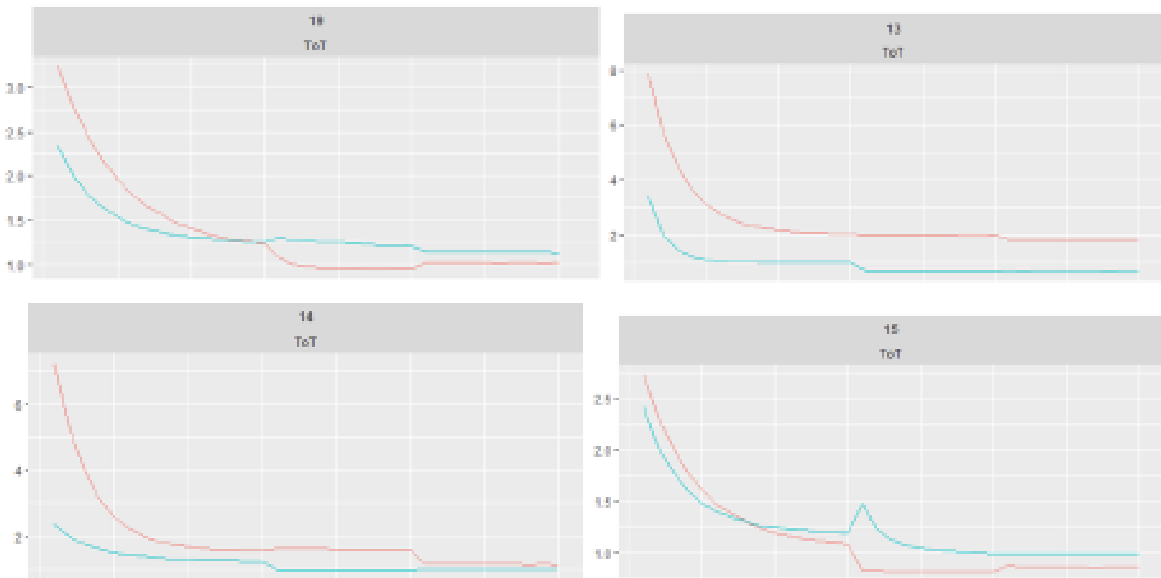


Figure 7. Three learning curves on individual-level displaying the outcome variable time on task. The x-axis depicts the number of trials while the y-axis displays the predicted seconds per trial. The blue line displays the Lifting and Grasping task and the red line the Cutting task. The learning curves display no decrease or a slight increase of time on task after the introduction of time pressure.

The same applies to the learning curves on the estimated outcomes of damage in the Lifting and Grasping task, which display a very consistent pattern. Usually, a significant increase in the number of errors during the time-pressure phase became apparent. Nonetheless, six participants showed no increase in errors but rather maintained the same number of errors over the time-pressure phase, without showing any observable differences in time-on-task in comparison to other participants (figure 8). However, the learning curves on the outcome of damage of the Cutting task show more variation than in the Lifting and Grasping task. The main pattern was similar to the one of the Lifting and Grasping Task, showing an increased amount of damage during the time pressure phase (figure 8). However, not all the individual learning curves show an increased number of errors during the time pressure phase. Since this observation may in some cases be related to the scaling of the y-axis, in the cases where the scaling does not affect the visualization of the curve, the error rate remains stable or decreases during the time pressure phase. Six participants showed obvious decreases in the error rate, while the decrease in time on task was no less than that of other participants.

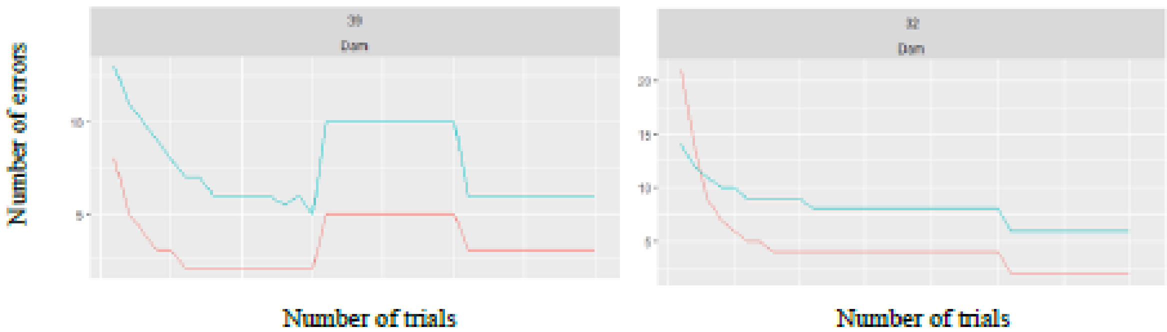


Figure 8. Displayed are four learning curves on participant-level of the estimated outcome variable damage. The blue line displays the Lifting and Grasping task and the red line the Cutting task. The left graph shows the usual course of the learning curve, while the right one shows an unusual one.

Comparing both outcomes of the tasks, it can be stated that both tasks largely confirm the findings at the population-level. Almost all the participant took less time during the time pressure phase in both tasks and remained with that speed afterward. In addition, an increased number of errors during the time pressure phase in both tasks could be observed. However, some participants showed no change or an increase in the number of errors during time pressure, not confirming the findings on the population-level. These observations stress the importance of examining the individual-level learning curves and indicate that not all participants reacted in the same way to time pressure. (Weimer, 2019, p19-21)

Appendix II. Score Form (example)

Participant Number	Phase	Comments / Observations
X	Initial	-
	Time Pressure	-
	Without TP	-

Demand:
"How mentally demanding was this trial? (Scale 1-10, 1 = lowest, 10 = highest)"

Trial	ToT	Errors	Error %	Demand
1	74,296	30	10	7
2	49,862	24	12	6
3	46,242	32	16	6
4	69,531	28	10	7
5	67,786	16	6	7
6	47,587	16	8	6
7	57,734	18	9	6
8	58,267	14	5	7
9	57,991	15	7	7
10	57,210	14	7	7
11	34,780	12	11	6
12	25,841	11	12	7
13	27,779	8	7	8
14	30,828	6	4	7
15	30,213	9	7	7
16	28,748	12	9	5
17	36,163	1	1	7
18	26,815	14	13	7
19	34,860	5	3	8
20	32,966	5	3	8

Appendix III. Buzz Wire Simulator; Arduino Program

WireV1.6

```
/*
  Programming BuzzWire.

  By Siebe Lorkeers
*/

//// GENERAL ////

// Variable for the number of milliseconds since the Arduino started
unsigned long currentTime = 0;


//// LCD SCREEN ////
// libraries
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

// Set LCD display
LiquidCrystal_I2C lcd(0x27, 16, 2);
const int LCDWidth = 16;
const int LCDHeight = 2;

   // Icon's
const byte clockIcon[] = {
  0x0E,
  0x11,
  0x15,
  0x15,
  0x17,
  0x11,
  0x11,
  0x0E
};

const byte finishFlagIcon[] = {
  0x1F,
  0x15,
  0x1B,
  0x15,
  0x1F,
  0x11,
```

```
  0x11,
  0x11
};

const int intervalLCD = 200;            // update the lcd display each 200ms
unsigned long previousTimeLCD = 0;       // timestamp last lcd update
bool redrawLCD = true;                  // indicates whether the LCD needs updating

// Results
bool resultUpdate = false;              // updates result page if true
const int intervalResult = 4000;         // update interval of results for the lcd display
unsigned long previousTimeResult = 0;     // timestamp last result update
unsigned long resultPage = 0;            // results page, 0 = trial time, 1 = amount of errors, 2 =  error
time percentage and error time count

  // results page timer
void resultPageTimer() {
  resultPage = resultPage +1;
  if (resultPage > 2) {
    resultPage = 0;
  }
  resultUpdate = true;
  redrawLCD = true;
}
  // reset result variables
void resultReset(){
  resultUpdate = false;
  resultPage = 0;
}


//// CONTACTS ////
const int intervalContactCheck = 20;       // time in milliseconds between checking contacts
unsigned long previousTimeContact = 0;    // timestamp last contact check

const int startPin = 2;              // the number of the start contact pin
int startState = LOW;               // state start contact
int startStatePrevious = LOW;        // last state start contact

const int wirePin = 3;              // the number of the wire contact pin
int wireState = LOW;               // state wire contact

const int endPin = 4;             // the number of the end contact pin
int endState = LOW;              // state end contact
int endStatePrevious = LOW;        // last state end contact
```

```
//// LED LIGHTS ////
const int startLed =  10;     // the number of the LED pin
const int wireLed =  11;     // the number of the LED pin
const int endLed =  12;     // the number of the LED pin


//// STOPWATCH ////
bool stopWatchActive = false;             // indicates whether the stopwatch is running
unsigned long stopWatchTime = 0;           // time in milliseconds when stopwatch started running
unsigned long stopWatchTimeElapsed = 0;    // elapsed time in milliseconds since stopwatch started
running

// Start stopwatch
void stopWatchStart() {
  stopWatchTime = currentTime;
  stopWatchActive = true;
  redrawLCD = true;
}

// Stop stopwatch
void stopWatchStop() {
  stopWatchTimeElapsed = currentTime - stopWatchTime;
  stopWatchActive = false;
  startStatePrevious = LOW;
  endStatePrevious = HIGH;
  previousTimeResult = currentTime;      // set time for resultpage timer
  redrawLCD = true;
}

// Reset stopwatch
void stopWatchReset() {
  stopWatchActive = false;
  stopWatchTime = 0;
  stopWatchTimeElapsed = 0;
  endStatePrevious = LOW;
  startStatePrevious = HIGH;
  redrawLCD = true;
}


//// ERRORS ////
bool errorActive = false;                // indicates whether a error is active
unsigned long errorInterval = 200;         // interval for error checking
unsigned long errorCount = 0;             // amount of errors
unsigned long errorTime = 0;             // time in milliseconds when error started
```

```
unsigned long errorTimeElapsed = 0;        // elapsed time in milliseconds since error started
unsigned long errorTimeCount = 0;          // total error time count
unsigned long errorTimePercentage = 0;     // errorTimeCount percentage of the trial time
(stopWatchTimeElapsed)

// Start error
void errorStart() {
  errorTime = currentTime;
  errorCount = errorCount + 1;
  errorActive = true;
}

// Stop error
void errorStop() {
  errorTimeElapsed = currentTime - errorTime;
  errorTimeCount = errorTimeCount + errorTimeElapsed;
  errorActive = false;
}

// Reset error
void errorReset() {
  errorActive = false;
  errorCount = 0;
  errorTime = 0;
  errorTimeElapsed = 0;
  errorTimeCount = 0;
}


//// Lay-Out ////
// Makes numbers under 10 get an extra 0, so 1 becomes 01, 5 becomes 05, etc.
String formatZeros(int number) {

  if (number < 10) {
    return "0" + String(number);
  } else {
    return String(number);
  }
}

// Makes the time in ms. a String eg "0: 01: 23.495" for 0 hours, 1 minute, 23 seconds and 495
hundredths
String formatTimeToString(unsigned long time) {

  unsigned long timeSeconds = time / 1000;      // convert the milliseconds into seconds by dividing by
1000
```

```
  int mSeconds = time % 1000;                  // the rest milliseconds what remains after sharing

  //int hours = timeSeconds / 3600;              // calculate the hours by dividing by 3600 (3600 seconds
= 60 seconds x 60 minutes)
  //int remainder = timeSeconds % 3600;          // calculate the remaining seconds by dividing by
3600. (3600 seconds = 60 seconds x 60 minutes)

  //int minutes = remainder / 60;                // calculate the minutes by dividing by 60 (1 minute = 60
seconds)
  //int seconds = remainder % 60;                // calculate the seconds by dividing by 60 (1 minute = 60
seconds)

  // Make from 9 -> "009" and from 87 -> "087"
  if (mSeconds < 10) {
    mSeconds = "00" + mSeconds;
  } else if (mSeconds < 100) {
    mSeconds = "0" + mSeconds;
  }

  return String(timeSeconds) + "." + String(mSeconds);
}

// Calculates how much space the LCD have to leave on the side to end up in the middle
int getMarginForCenter(String text, int offset) {
  int margin = LCDWidth - (text.length() + offset);
  return margin / 2;
}

//// Function to check contact state ////
void checkContactState() {

  // If the time difference with the previous readout is greater than intervalContactCheck
  if (currentTime - previousTimeContact > intervalContactCheck) {

    // read the state of the contacts (LOW/HIGH)
    startState = digitalRead(startPin);
    wireState = digitalRead(wirePin);
    endState = digitalRead(endPin);

    // at start arduino
    if (startStatePrevious == LOW && endStatePrevious == LOW) {
      stopWatchActive = false;
    }

    // when the ring is at start (start contact)
    if (startState == HIGH) {
```

```
    stopWatchReset();
    errorReset();
    resultReset();
    digitalWrite(startLed, HIGH);    // turn LED on
  } else {
    digitalWrite(startLed, LOW);      // turn LED off
  }

  // when the ring leaves start and stopwatch is inactive
  if (startState == LOW && startStatePrevious == HIGH && !stopWatchActive) {
    stopWatchStart();
    Serial.print("Start! Error Interval:");
    Serial.print(errorInterval);
    Serial.print("  Current Time: ");
    Serial.println(currentTime);
  }

  // when the ring contacts the wire (wire contact)
  if (wireState == HIGH && !errorActive && stopWatchActive) {
    errorStart();
    Serial.print("Error:");
    Serial.print(errorCount);
    Serial.print("  Current Time: ");
    Serial.println(currentTime);
  }

  // turn LED (and bell) on when the ring contacts the wire
  if (wireState == HIGH && stopWatchActive) {
    digitalWrite(wireLed, HIGH);
  } else {
    digitalWrite(wireLed, LOW);      // turn LED off
  }

  // when the ring loses contacts the wire
  if (wireState == LOW && errorActive == true) {
    if (currentTime - errorTime > errorInterval){    // set error interval to prevent counting minor
vibrations as seperate errors
      errorStop();
    }
  }

  // when the ring is at the end (end contact)
  if (endState == HIGH && stopWatchActive) {
    stopWatchStop();
    Serial.print("End! Errors: ");
    Serial.print(errorCount);
```

```
      Serial.print("  Current Time: ");
      Serial.println(currentTime);
    }

    // turn LED on when the ring is at the end, and keep LED on till reset at start
    if (endState == HIGH || endStatePrevious == HIGH) {
      digitalWrite(endLed, HIGH);
    } else {
      digitalWrite(endLed, LOW);      // turn LED off
    }

    // save the current time in previousTimeContact
    previousTimeContact = currentTime;

  }
}


//// Function to update LCD screen ////
void updateLCD() {

    // If the time difference with the previous readout is greater than intervalLCD
  if (currentTime - previousTimeLCD > intervalLCD) {

    // Update result page number for given interval if results are been showed.
    if ((currentTime - previousTimeResult > intervalResult) && endStatePrevious == HIGH) {
      resultPageTimer();
    }

    if (redrawLCD || stopWatchActive || resultUpdate) {

      lcd.clear();

      // at start arduino
      if (startStatePrevious == LOW && endStatePrevious == LOW) {
        lcd.setCursor(2, 0);              // set cursor on position 2, line 1
        lcd.print("GO TO START!");
    }

      // when the ring is at start (start contact)
      if (startState == HIGH) {
        lcd.setCursor(1, 0);              // set cursor on position 1, line 1
        lcd.print("START IF READY");
        lcd.setCursor(3, 1);              // set cursor on position 3, line 2
        lcd.print("GOOD LUCK!");
      }
```

```
    // When the stopwatch is running (during trial)
    if (stopWatchActive) {

      // Calculate the elapsed time and format that time
      String formattedTime = formatTimeToString(currentTime - stopWatchTime);

      // Calculate the center for the text with getMarginForCenter (formattedTime, 4)
      lcd.setCursor(getMarginForCenter(formattedTime, 4), 0);

      lcd.write(0);             // draw the clock icon from memory position 0
      lcd.print(" ");           // write a space
      lcd.print(formattedTime);   // write the elapsed time
      lcd.print("ms");           // write ms
    }

    // When the stopwatch is stopped (end trial)
    if (!stopWatchActive && endStatePrevious == HIGH) {

      // if resultPage is 0, show trial time
      if (resultPage == 0){
        lcd.setCursor(3, 0);                         // set cursor position 3, line 1
        lcd.print("Trial time");
        lcd.setCursor(getMarginForCenter(formatTimeToString(stopWatchTimeElapsed), 2), 1);    //
Calculate the center for elapsed stopwatch time
        lcd.write(1);                               // draw finish icon from memory position 1
        lcd.print(" ");
        lcd.print(formatTimeToString(stopWatchTimeElapsed));   // write formatted stopwatchtime
        resultUpdate = false;
        previousTimeResult = currentTime;                 // set previous result update time
      }

      // if resultPage is 1, show amount of errors
      if (resultPage == 1){
        lcd.setCursor(4, 0);                         // set cursor position 4, line 1
        lcd.print("Errors:");
        String errorCountF = String(errorCount);             // format error count to string for
getMarginForCenter function
        lcd.setCursor(getMarginForCenter(errorCountF, 2), 1);   // Calculate the center for the
formatted error count
        lcd.print("# ");
        lcd.print(errorCountF);                        // write formatted error count
        resultUpdate = false;
        previousTimeResult = currentTime;                 // set previous result update time
      }
```

```
      // if resultPage is 2, show time count errors and corresponding percentage of trial time
      if (resultPage == 2){
        lcd.setCursor(0, 0);                        // set cursor position 1, line 1
        lcd.print("Error time: ");
        errorTimePercentage = round(((float)errorTimeCount /  (float)stopWatchTimeElapsed) * 100.0);
// calculate error time percentage from total trial time
        lcd.print(errorTimePercentage);                // write calculated percentage number
        lcd.print("%");
        lcd.setCursor(getMarginForCenter(formatTimeToString(errorTimeCount), 0), 1);  // Calculate
the center for the text with getMarginForCenter (errorTimeCount, 0)
        lcd.print(formatTimeToString(errorTimeCount));   // write formatted errorTimeCount
        resultUpdate = false;
        previousTimeResult = currentTime;              // set previous result update time
      }

      // Update result page number for given interval.
      if (currentTime - previousTimeResult > intervalResult) {
        resultPageTimer();
        previousTimeResult = currentTime;
      }
     }
     redrawLCD = false;
   }

   // save the current time in previousTimeLCD
   previousTimeLCD = currentTime;

  }
}

//// SETUP ////
void setup() {
  // Set serial monitor
  Serial.begin(9600);

  // initialize the LED pin as an output:
  pinMode(startLed, OUTPUT);
  pinMode(wireLed, OUTPUT);
  pinMode(endLed, OUTPUT);

  // initialize the contact pins as an input:
  pinMode(startPin, INPUT);
  pinMode(wirePin, INPUT);
  pinMode(endPin, INPUT);

  // initialize LCD
```

```
  lcd.init();                      // initialize LCD screen
  lcd.backlight();                 // switch backlight on
  lcd.createChar(0, clockIcon);        // define symbol in memory position 0
  lcd.createChar(1, finishFlagIcon);    // define symbol in memory position 1

}

//// LOOP ////

void loop() {

  currentTime = millis();           // save current time
  checkContactState();              // check current contact state
  updateLCD();                      // Update LCD screen

}

//// Kind regards Siebe Lorkeers ////
```

Appendix IV. Programming tests

Test 1: Study Contact Interval (35ms and 250ms)

Start! Contact interval:35 Current Time: 298132
Error:1 Current Time: 299418
Error:2 Current Time: 299490
Error:3 Current Time: 310718
Error:4 Current Time: 311121
Error:5 Current Time: 311321
Error:6 Current Time: 311523
Error:7 Current Time: 311631
End! Errors: 7

Start! Contact interval:35 Current Time: 327687
Error:1 Current Time: 338987
Error:2 Current Time: 342097
Error:3 Current Time: 346723
Error:4 Current Time: 346888
End! Errors: 4

Start! Contact interval:35 Current Time: 365407
Error:1 Current Time: 376089
Error:2 Current Time: 376528
Error:3 Current Time: 380716
Error:4 Current Time: 381227
Error:5 Current Time: 381793
Error:6 Current Time: 388561
Error:7 Current Time: 392418
Error:8 Current Time: 395637
Error:9 Current Time: 396606
Error:10 Current Time: 397117
End! Errors: 10

Start! Contact interval:35 Current Time: 409717
Error:1 Current Time: 428093
Error:2 Current Time: 428423
Error:3 Current Time: 428752
Error:4 Current Time: 429099
Error:5 Current Time: 429228
Error:6 Current Time: 429300
Error:7 Current Time: 429465
Error:8 Current Time: 429759
Error:9 Current Time: 429960
Error:10 Current Time: 430232

Error:11 Current Time: 430304
End! Errors: 1

Start! Contact interval:35 Current Time: 442043
Error:1 Current Time: 443637
Error:2 Current Time: 443839
Error:3 Current Time: 443911
Error:4 Current Time: 450879
Error:5 Current Time: 451116
Error:6 Current Time: 451720
Error:7 Current Time: 451792
Error:8 Current Time: 451957
End! Errors: 8

Start! Contact interval:250 Current Time: 82533
Error:1 Current Time: 95861
Error:2 Current Time: 97370
End! Errors:

Start! Contact interval:250 Current Time: 271308
Error:1 Current Time: 288154
Error:2 Current Time: 302736
Error:3 Current Time: 309776
Error:4 Current Time: 312038
Error:5 Current Time: 313548
Error:6 Current Time: 316816
Error:7 Current Time: 318827
Error:8 Current Time: 322600
Error:9 Current Time: 323354
Error:10 Current Time: 324611
Error:11 Current Time: 325113
Error:12 Current Time: 326372
End! Errors: 12

Start! Contact interval:250 Current Time: 387406
Error:1 Current Time: 409292
Error:2 Current Time: 415578
Error:3 Current Time: 416834
Error:4 Current Time: 417338
Error:5 Current Time: 420606
Error:6 Current Time: 421862
Error:7 Current Time: 426891
Error:8 Current Time: 427395
Error:9 Current Time: 428400
Error:10 Current Time: 429910
End! Errors: 10

Start! Contact interval:250 Current Time: 462291
Error:1 Current Time: 473355
Error:2 Current Time: 479642
End! Errors: 2

Start! Contact interval:250 Current Time: 541420
Error:1 Current Time: 552506
Error:2 Current Time: 561054
Error:3 Current Time: 572369
Error:4 Current Time: 574381
Error:5 Current Time: 574883
End! Errors: 5

Test 2: Study Error Interval (New variable in code, 200ms and 500ms)

Start! Error Interval:200 Current Time: 319748
Error:1 Current Time: 349834
Error:2 Current Time: 354382
Error:3 Current Time: 356770
Error:4 Current Time: 357146
End! Errors: 4

Start! Error Interval:200 Current Time: 396111
Error:1 Current Time: 400996
Error:2 Current Time: 410754
Error:3 Current Time: 417340
Error:4 Current Time: 421363
Error:5 Current Time: 421738
End! Errors: 5

Start! Error Interval:200 Current Time: 448583
Error:1 Current Time: 452514
Error:2 Current Time: 459003
Error:3 Current Time: 464959
Error:4 Current Time: 466846
Error:5 Current Time: 468228
End! Errors: 5

Start! Error Interval:200 Current Time: 507213
Error:1 Current Time: 517658
Error:2 Current Time: 519573
Error:3 Current Time: 532621
Error:4 Current Time: 532848
Error:5 Current Time: 534430

Error:6 Current Time: 534886
End! Errors: 6

Start! Error Interval:200 Current Time: 548790
Error:1 Current Time: 549718
Error:2 Current Time: 549970
Error:3 Current Time: 573505
Error:4 Current Time: 573978
Error:5 Current Time: 574310
Error:6 Current Time: 575464
Error:7 Current Time: 576996
End! Errors: 7

Start! Error Interval:200 Current Time: 597028
Error:1 Current Time: 612501
Error:2 Current Time: 613330
Error:3 Current Time: 615213
Error:4 Current Time: 622409
Error:5 Current Time: 625575
Error:6 Current Time: 626957
Error:7 Current Time: 627184
Error:8 Current Time: 628618
End! Errors: 8

Start! Error Interval:500 Current Time: 67917
Error:1 Current Time: 85961
Error:2 Current Time: 87868
Error:3 Current Time: 103634
Error:4 Current Time: 104439
Error:5 Current Time: 107684
End! Errors: 5 Current Time: 113037

Start! Error Interval:500 Current Time: 138246
Error:1 Current Time: 158618
Error:2 Current Time: 160585
End! Errors: 2 Current Time: 164250

Start! Error Interval:500 Current Time: 179026
Error:1 Current Time: 185448
Error:2 Current Time: 188641
Error:3 Current Time: 189926
Error:4 Current Time: 193694
Error:5 Current Time: 203428
Error:6 Current Time: 204880
Error:7 Current Time: 206945
End! Errors: 7 Current Time: 211317

Start! Error Interval:500 Current Time: 207926
Error:1 Current Time: 243753
Error:2 Current Time: 245187
Error:3 Current Time: 252830
End! Errors: 3 Current Time: 258690

Start! Error Interval:500 Current Time: 274893
Error:1 Current Time: 278753
Error:2 Current Time: 286746
Error:3 Current Time: 296226
End! Errors: 3 Current Time: 302993

Start! Error Interval:500 Current Time: 319547
Error:1 Current Time: 353377
End! Errors: 1 Current Time: 357348