Developing a low-cost driving simulator and the physical components effect on validity

SW10 master thesis by d615a

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Title
Developing a low-cost driving simulator and the physical components effect on validity

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Abstract
This master thesis deals with the question: *What is important when developing and validating a driving simulator?*

First we deal with the question: *What are the challenges and problems of developing a low-cost driving simulator?* This concerns finding which possibilities you have when developing a driving simulator, and testing the simulator in order to find the main problems with it.

We also deal with the question: *How do the different physical components of a driving simulator affect the validity?* This concerns developing test scenarios in order to test the relative validity of physical components based on different dependent variables.

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Preface

This paper contains the master thesis developed by group d615a at Department of Computer Science, Aalborg University. The research started in fall 2010 where a group developed a driving simulator and wrote a report describing the implementation and a subsequent experiment in the simulator. Therefore some of the results used in article 1 in this master thesis are based on a common experiment from this group.

In spring 2011 the group was split up in compliance with the curriculum, whereas the authors of this master thesis are two members of this former group.

We would like to thank our supervisor, Jan Stage, for his help and effort during the entire process of this master thesis. Furthermore we would like to thank all the test subjects participating in our experiments, both in the fall 2010 and spring 2011.

When a reference to cited material is made, it will be displayed as a number in square brackets after the sentence or word, as such:[6]. When referring to implementation features or classes these are highlighted using the *italic* format. When code is referred it is framed in listings such as displayed in listing 1:

Listing 1: *path/to/file* - The `codeExample` function.

```
Code example
```

The bibliography can be found in chapter 5.

Signatures

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Rene Bach Gustafson

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1 Introduction

Driving simulators are used to simulate scenarios designed to portray reality in the best possible way. A common problem with driving simulators is often how much effort you need to put into developing the simulator, in order to get a realistic representation of a real world scenario.

Many previous articles have been concerned about developing driving simulators, where a lot of effort has been put into developing advanced components like motion control, specifically improving realism of sound, creating a 360 degree viewing angle etc. [3; 1; 4]

An interesting question to the advanced setups would be whether they are superior to a driving simulator without all the advanced components. This is an important topic since advanced driving simulators are costly, with the most advanced driving simulator in the world costing about 50 million dollars, measuring more than 550 square meters. [5] Since expanding a driving simulator with advanced components is very costly, it would be preferable to find a way of testing the effect of these components.

The overall research question for this master thesis is: "*What is important when developing and validating a driving simulator?*". Enclosed with this summary are two articles, one dealing with the development of a driving simulator and the other dealing with the validity of the individual physical components of a driving simulator.

The first article deals with the question: "*What are the challenges and problems of developing a low-cost driving simulator?*" It describes the development of a driving simulator using Unity 3D and the problems found with the simulator in a lab-experiment.

The second article deals with the question: "*How do the different physical components of a driving simulator affect the validity?*" It describes the validation of a driving simulator and evaluates different physical components of the simulator in order to find their influence on validity. In this article we develop a specific environment to measure validity by looking at different dependent variables.

2
Article Overview

In this chapter a summary of the articles forming the master thesis is given to provide an overview of the research and findings from each article.

2.1 Article 1

In this article the implementation of a low-cost driving simulator, and the challenges and problems encountered during the process was examined. The driving simulator was developed in the game development tool, Unity 3D, using an open source project with some basic car physics. The existing car physic was adjusted and refined together with the addition of the ability to control with steering wheel and pedals, including a clutch.

A driving environment with buildings and roads was created in CityScape, and autonomous vehicles and pedestrians were implemented as dynamic objects in the environment. Data collection mechanisms were also implemented to measure information about time, speed, lateral deviation and values of the steering wheel and pedals.

An experiment was set up, where the test subjects were able to comment on the main problems they found in the driving simulator in terms of realism. Questions about the driving simulator were answered through a subsequent interview, concerning both the physical and software aspects of the simulator.

The results contributed with comments about problems and even possible solutions in order to improve the driving simulator. The most important and repeated of these problems were outlined to give an overview of the improvements necessary, to make the simulator a potential substitution for real driving in research purposes. On the physical side, problems with abnormalities in the steering wheel and pedals, and lack of motion in the simulator were present. While on the software side the sound, graphics and better implementation of gear shift and clutch, contributed to the list of problems.

2.2 Article 2

In this article the driving simulator described in article 1, was used in order to test the validation of different physical components. Physical components were added (BassShakers and widescreens) and software components (test track and city environment), together with the implementation of a new car physic, logging system, BassShaker system, data handling system and GameController.

Four experiments were performed to be able to test the relative validity of different physical components of the simulator (experiment 1,2 and 3), and the full simulator setup compared to a minimal setup (experiment 4). The relative validity is concerned about the correspondence between different components, meaning that two components would be relative valid if they produce relative uniform results. Experiment 1 investigated the relative validity between steering wheel and pedals and keyboard through 3 tasks (slalom course, braking distance track and runaway with moving obstacles). Experiment 2 looked at the relative validity between starting and stopping the car with or without BassShakers, while experiment 3 studied whether the speed was easier to assess with or without side windows. Experiment 4 was performed in order to test the relative validity between using a full simulator setup compared to a minimal setup (laptop).

The results showed that in some test scenarios we would have relative validity between e.g. using a keyboard or a steering wheel, whereas other test scenarios would not be relative valid between keyboard and steering wheel. Also the age groups had a huge impact on relative validity, where a relative valid result could be connected to only a specific age group, and especially the young had many relative valid results between keyboard and steering wheel. We found that relative validity is connected to which type of test scenario, age group and dependent variable used.

3
Research Method

This chapter is based on [2, Ch. 2-3] and [6].

Tightly coupled to the research method is the purpose of the research. The research purpose of our research is "Evaluation" and according to [6] defined as: *"Evaluation, which includes assessment, validation, and assurance actions, is the systematic study of a product to determine its usefulness and/or affect. Evaluations can be individual studies to determine if some feature works; can compare a product with another product; or can study large group of users to determine if some feature have some properties such as usefulness, ease of use, etc."*

The reason for choosing a lab-based experiment, stems of course from the fact that it was a driving simulator we were going to develop and later on use to perform the experiments. A driving simulator is traditionally build in a laboratory, which will also ease the collection of driving data and ensure a repeatable execution of the driving scenarios used in the experiments.

The study can be categorized as experimental research using a lab-based experiment, because different conditions in the experiment was directly compared (dependent variables) while other factors were kept the same (independent variables).

A lab experiment is considered to have the following advantages:

- **Reliability:** Taking place in a controlled environment, a lab experiment is considered highly reliable since it is not influenced by external disturbances. This reliability will also be present in our experiments, as the simulator is build in a usability lab and will be free of outer disturbances.
- **Variable control:** In a lab experiment the experimental control and manipulation of variables before and during the experiment is easy to control. The variable control is highly present in our testing environment, as scenarios is easy to change while the components of the simulator are still unchanged.
- **Replicable:** Having control of the variables in a steady environment, makes a lab experiment highly replicable in terms of repeating the ex-

act same experiment. In the experiments we are able to replicate each experiment between the test subjects which ensures the consistency of keeping the conditions the same.

- **Data collection:** Running the experiment in a controlled environment ensures precise and reliable measures, and enables an easier integration and control of data collection equipment like cameras, microphones and computer logged data. By placing our driving simulator in a lab collecting data is much easier as cameras and microphones are an integrated part and are easily adjusted to record what we find important in the experiment.

Among the disadvantages and limitations of a lab experiment are:

- **Unknown generalizability:** It is hard to tell whether the results from the lab experiments can be generalized to results outside the laboratory, because a laboratory setting usually not account for variables which could have an influence in the real world. As our simulator has not been tested towards driving in a real car, but instead in the opposite direction, it is unclear whether a validation between a minimal and full simulator setup, also would result in validity between a full simulator setup and real driving.

- **Limited realism:** The relation to the real world is often limited because of the artificial setting in a lab experiment, which result in lack of variables and interruptions that might have an impact on the results. As a driving simulator is a artificial representation of real driving, it is quite likely that there are some differences in the two environments regarding sensory input and the handling of the car. These differences could result in test subjects acting differently from how they drive a real car and maybe they would not be as cautious as they would have been driving in a real environment.

- **Being observed:** A lab-based experiment may not give the right picture of a test subject's normal behavior and interaction, because they feel stress about being observed and being in an unfamiliar environment. This is commonly known as the "Hawthorne effect". Related to the limited realism the test subjects might also react differently than driving in a real car due to the fact that they feel stressed about being observed and assessed. This would maybe cause the test subjects to be too cautious or generally drive different than they are used to.

To reduce the unknown generalizability, looking at related research of validating a driving simulator towards real driving could help us focus on the same measurements and areas in our study and thereby increase the possibility of generalizability towards real driving.

The problem with limited realism could be reduced by investigating what test subjects find important, in order to reduce the differences between driving in the simulator and a real vehicle. This could be solved by implementing improvements to the simulator according to the problems found, and thereby settle the differences between the environments further.

By letting the test subject know that it is not them being tested and they are allowed to stop the test at any time, could possibly help reducing feeling stress about being observed.

When designing an experiment, the question whether to use a between-group or within-group, or a combination of both is an important subject. In this experiment we have chosen to use a within-group design because of the following advantages:

- Smaller sample size.
- Effective isolation of individual differences.
- More powerful tests.

A smaller sample size will reduce the costs and problems of acquiring a large number of test persons to the experiment. Isolating the individual differences, will ensure that a group of test subjects who do particularly well or bad in a condition, are exposed to all conditions in a within-group experiment and the experiment can therefore not be biased by this one special condition or group. The more powerful tests makes it easier to get statistically significant results compared to the between-group, because of the smaller sample size and individual differences not having an impact on the results.

The within-group design also has some possible disadvantages (of which the opposite represents the advantages of between-group):

- Hard to control learning effect.
- Large impact of fatigue.

Another aspect of using within-group, which also is present in our experiment, is keeping a complete randomization within the same experiment in a manner that each test subject is assigned to the various conditions in a random order. By using a effective randomization of the tasks we will minimize the impact of the learning effect, and keeping the test session under a hour will also minimize the importance of fatigue.

4
Conclusion

In this master thesis an implementation of a low-cost driving simulator was conducted together with two experiments. The first experiment was investigating the overall experience to find problems and possible improvements for a later version of the simulator. In the second experiment a number of different physical components were tested for their impact on relative validity and finally a minimal setup was tested towards a full simulator setup.

What are the challenges and problems of developing a low-cost driving simulator? The main challenge of developing a low-cost driving simulator, is to keep the costs at a sufficiently low level, while still being able to develop an acceptable driving simulator in terms of being usable for research purposes. This challenge is solved in a number of ways depending on the specific requirements and the purpose of the simulator.

In our approach, building new simulator software on the basis of an existing car physic, showed to be the right solution, because it supported our requirements of being able to add and modify every aspect of the driving simulator. Beyond this, using student versions of rapid development software, limited the costs, to the time spent on developing. Likewise the physical components were also kept at a minimum by building the simulator on foundation of euro pallets and keeping the total cost approx 2170 USD.

To investigate problems in the simulator, an experiment was set up to let test subjects evaluate the simulator based on their own experience. The problems were found through a subsequent interview, where questions about both physical and software components were related to realism and real driving. From this we found that problems with the steering mechanisms and the lack of motion while driving, were important issues related to the physical components. Realistic sound and a realistic implementation of gear shift and clutch, were important aspects of optimizing the software of a driving simulator.

How do the different physical components of a driving simulator affect the validity? Each different physical component of a simulator is contributing to the realism of a driving simulator to a greater or lesser extent.

This contribution could be increased/decreased, with the addition/elimination or improvements of a physical component.

To answer the question an experiment was set up to investigate how physical components mutual affected the validity of our simulator. In the experiment, scenarios for testing physical components including steering wheel vs. keyboard, vibrations on/off and side windows on/off were created. Furthermore a full simulator setup was compared to a minimal setup with only a laptop running the simulator software.

We found that whether having a driving simulator with or without side windows, or vibrations in the form of BassShakers did not seem to affect the validity. Impact on the validity was instead found in scenarios when comparing steering wheel and keyboard, and between the full and minimal simulator setup. Even though relative validity was obtained in some conditions and for some dependent variables, the results showed that other dependent variables contradicted the relative validity. This indicated that the validity of a simulator was related to a number of aspects like age, scenario and the dependent variables.

What is important when developing and validating a driving simulator? When developing a simulator, it is important to let the development be guided by what the usage of the simulator is aimed at. In some cases, existing driving simulators or even existing driving games could possibly be used, whereas other goals of usage require building a totally customized simulator from scratch. With the goal of the simulator in mind, you avoid ending up in a situation where a simulator is unsuitable or even useless in terms of its planned use.

The same aspect applies to validating a simulator, where it also is important to determine what the usage of the simulator is aimed at. This matter is consistent with the results found, as we discovered a number of aspects to be considered when talking about validity. As an example, if the simulator is developed for speed research, it is possible to validate the simulator for this use, by using speed as the only or at least the most important dependent variable. Even though other aspects of the driving simulator does not comply to validate between the simulator and real driving they are in this case not of special interest.

Among the limitations from this paper are the unknown generalizabilty, limited realism and the problem about being observed, which is further examined in chapter 3.

In order to take the research further, improving the simulator would still be a subject of matter. From our interview with the test subjects, a number of improvements to the simulator were still desired to create an experience more like real driving. Especially on the sound side a big part of the test subjects commented, that there were some shortcomings, e.g. with the engine sound.

Furthermore to investigate whether the results from our study could be generalized to apply for real driving, and not just between the minimal and full simulator setup, setting up an further experiment, to find whether a relative validity between the simulator and real driving existed, would be necessary.

5
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Developing a Low-Cost Driving Simulator: Challenges and Problems

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ABSTRACT
In this study a low-cost driving simulator was implemented by using the game development tool, Unity 3D, and the environment tool, CityScape. An experiment was set up to investigate problems in the simulator, together with the overall experience reported by the test subjects. Results were based on a subsequent interview where the test subjects answered questions about their thoughts on the simulator and its realism and how to improve it. The results from the interview provided a number of mixed comments from the test subjects of both positive and negative character. From these comments the most reported and important problems were listed to give an overview of the possible improvements to be implemented in a future version of the simulator.

Author Keywords
Driving simulator, laboratory test, low-cost.

INTRODUCTION
A driving simulator is an operation unit, which allow the user to interact with a computer screen in a way as close to the real world as possible. Different levels of driving simulators can be used, from the very advanced driving simulators with motion control and a 360 degree viewing angle, to simple fixed-base driving simulators with a single screen in front of the user.

A driving simulator can be used to fulfill different purposes, such as evaluation of new vehicles in the car industry, testing of new in-vehicle assistance systems or education. Different reasons exist for using a driving simulator, some of these are that it is a lot safer than testing in a real world driving situation, it can be easier to collect driving data from each test, it is a cheaper way of testing new in-vehicle systems and it gives the option to reconstruct specific driving situations.

A previous study by Bach et al. indicated that simulated driving led to many similar results compared to real driving. Overall the experiment indicated that the controlled driving had higher costs in terms of time used on the experiment, analysis of data, and economy. This indicates that simulated driving is worth considering especially when you have to develop a low budget experiment.[2]

When developing a driving simulator, you have to decide on how advanced the setup should be. Based on general assumption, one would expect that a very advanced driving simulator would give the best results in terms of realism. But the very advanced driving simulators are also very costly and require a huge amount of man-hours to construct and maintain. Therefore you often have to consider how advanced a driving simulator you need, in order to fulfill your testing purposes.

This article describes the development of a driving simulator, and evaluates the users' experience from driving it. The goal was to develop a driving simulator on a low budget, which would be capable of giving a realistic feeling from both the setup and software point of view.

In the following sections a survey of related work is provided, followed by a description of the implementation, the method used and results found in the experiment and finally rounded off with a conclusion.

RELATED WORK
When developing a driving simulator, developers are left with three approaches to create a driving simulator suitable for testing purposes. These three options are:

- Developing from scratch.
- Modifying an open source project.
- Building in an existing virtual world.

Developing from scratch
In [7], the simulator was developed from scratch with a constructed database generating different parts of the simulator on the fly. The visual representation of the database was created with reasonable cost and was able to run on a single PC. In this way the road, houses, traffic, etc. were presented from an overall model according to the cars current position in the virtual environment.

Another example of a driving simulator developed from scratch is found in [10], where the simulator was build upon a number of APIs giving the developers access to resources of

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graphics and sounds for the simulator. [10] focused on presence and arousal and emphasized the perception of the environment as a contributory factor to the feeling of being ”inside” a virtual environment through the simulator.

Modifying an open source project

As an alternative approach, starting from an open source project, e.g. an existing driving game or simulator, is also a possibility. By modifying or creating extensions to the existing code developers will have a cost-effective method to design a driving simulator the way they want.

This method was used in [13], where they tried to create a realistic driving simulator on a low budget, relying on off-the-shelf hardware. Along with off-the-shelf hardware, an existing driving game was used with options to design cars and lanes, adjust camera angles and with an extensible plug-in API able to log data about position and speed. The use of a driving game imposed restrictions on the freedom to e.g. manipulate with the traffic or adding new elements like road signs and traffic lights, but despite this it was considered a quick and cost-effective way to design a driving simulator for testing purposes.

Building in an existing virtual world

The last approach is to create a simulator in an existing virtual world, and build it together with existing objects.

Such an approach to develop a driving simulator took place in [6], where a functional driving simulator was implemented in the online virtual 3D world, Second Life. By using the graphical motor of Second Life containing data about gravity and collisions between objects in the 3D-world, a vehicle can be scripted to maneuver in the virtual world and simultaneously comply with the physical laws of the world. Furthermore both static objects, e.g. road signs, and dynamic objects, e.g. autonomous vehicles, can easily be added and used as a part of the driving simulator because they already exist as objects in the virtual world. This approach will according to [6], be a valuable method for rapid development of a driving simulator to be used in testing purposes, where the requirements for the degree of adaptation is moderate and a more realistic and expensive simulator is not necessary.

Improving specific parts of the simulator

Attention could also be on improving parts of an existing simulator or when developing a simulator have a greater focus on a specific part, to improve the overall experience and reflect the reality in the driving simulator.

This focus was present in [11] where Mourant and Refsland were working with the soundtrack of the driving simulator. Among the additions of sound were varying engine noise and tire squealing of the human-controlled vehicle and of autonomous vehicles. In addition to this vehicle wind noise, beeping of the vehicles’ horns, clicking of activated turn signals and noise when vehicles collide were also added. Furthermore sirens from emergency vehicles was included and modeled to obey the rules of the Doppler Effect.

Another article, [1], described how a framework to model human-like driving behavior among the autonomous vehicles present in the driving simulator was developed. The model was grouped into four stages each taking care of a part of the decision-making process and afterwards implement actions from this in the traffic. First the driver’s current perceptions were intercepted, and then the model described how the driver emotionally reacted to this in the environment. Next the model tried to find a decision to satisfy the drivers emotionally requirements. Finally the model tried to implement these decisions, as soon as it was safe enough to implement the decision in the environment. Beyond these different stages, the autonomous vehicles were given various human-like characteristics which would affect the different stages of the model. To make the autonomous vehicles more human-like, the model could imitate both aggressive and cautious drivers, but also tired or intoxicated drivers could be modeled. This will according to [1] make the simulator appear more unpredictable and contribute to the realism of the simulator.

Driving settings and measures

To get an idea of which measures have been used in previous driving experiments, and under which settings these experiments have been carried out, a literature survey of existing papers could help getting a comprehensive overview.

[4] was written on the basis of such a literature survey where 100 papers were investigated to find how in-vehicle systems were evaluated, and how attention was measured in the use of these systems. To group the articles, 4 different categories for driving settings were outlined: No driving, simulated driving, controlled driving and real traffic driving, and 5 categories for the attention measures: Primary task performance, secondary task performance, eye glance behavior, physiological measures and subjective assessments. The grouping showed that most studies were performed in simulated driving or real traffic driving, while lateral and longitudinal control (primary task performance) and eye glance behavior were the most frequent used measures.

Simulated driving vs. real driving

To the question whether a driving simulator was useful in relation to real driving an experiment is set up in [2] to compare driving on a closed driving facility (controlled driving) with driving in a simulator. The goal of the experiment was to find similarities and differences between the two methods of testing, and look at the costs associated with them, to find whether it was worthwhile to test systems in a real car rather than just the simulator. Results showed that the driving settings led to many similar results, but controlled driving resulted in longer and more frequent eye glances, and that driving errors were more common in the simulated driving. Bach et al. suggested that the longer eye glances, could show that the test persons felt in control of the situation and therefore allowed themselves to keep eyes off the road for a longer period of time. Looking at the greater amount of driving errors in simulated driving, Bach et al. suggested this may be due to the lack of sensory input during driving, which would occur in their ability to keep velocity and feel present in the driving. In addition to these results it appeared that controlled driving had higher costs in terms of time used on the experiment (114 vs. 50 hours) and analysis of data (181 vs. 112 hours), and economy where renting a track and vehicle resulted in greater expenses.

IMPLEMENTATION

In the implementation, the different steps of developing the low-cost driving simulator are described, from the choice of development tools to a thorough survey of the implemented functionality supported by code examples.

Instead of starting from scratch, we used an open source project developed by Unity Studios together with the development tool called Unity 3D. The open source project already had some of the basic functionalities implemented like the car physics, which we were able to make use of. This gave us the benefit of having total freedom to develop whatever functionalities we wanted by using the Unity 3D development tool, while still being able to reuse some of the essential functionalities we needed from an existing open source project.

Unity 3D is a game development tool, which is designed in a way such that developing graphical environments is as easy as possible. It comes with a combined opportunity of being able to change the graphical environment using an editor, or by manipulating directly with the environment in a graphical view using the mouse. This enables the developer to keep being productive, since the developer always has a graphical view from which all the changes made through the editor can be seen directly and on the fly.

In addition to the existing functionality in Unity 3D we needed to implement:

- Car physics
  - Steering wheel and pedals.
  - Clutch.
- Data collection
- Driving environment
  - Autonomous vehicles.
  - Pedestrians.

Car physics

Even though Unity 3D offered a car physic where we were able to adjust a number of parameters to let the car behave as a real car, there were some things left to implement. First of all we had to add the option of using steering wheel, gear shift and pedals as input devices.

Steering wheel and pedals

To add the steering wheel and pedals, we had to make changes to the *CarController* class which contains all the keyboard controls used to control the car. Therefore we added a Boolean attribute called *KeyboardControl* to the script, to toggle between using the steering wheel and pedals and the keyboard as input device.

Next we made some changes to the *steering*, *brake*, *clutch* and *throttle* values such that they were represented by the function *Input.GetAxis()* which represented the steering wheel and pedals. A link between the inputs from the steering wheel and pedals to the correct *Input.GetAxis()* function was made in Unity 3D preferences, in order to ensure that Unity 3D was able to recognise all the inputs.

To ensure an easier way of analysing the values of the steering wheel and pedals, we implemented a script which displayed detailed information about the joystick values. This script helped us when we were to implement changes to the car physics, where information about clutch, throttle and brake values were very important. We implemented the script by using different GUI functions from Unity 3D. The GUI functions were able to give a graphical representation of the different values from the steering wheel and pedals. As an example the horizontal values of the steering wheel was represented by a function called *GUI.HorizontalSlider* and the vertical throttle value from the pedal was represented by *GUI.VerticalSlider*. On figure 1 an image of the GUI box we implemented is shown.

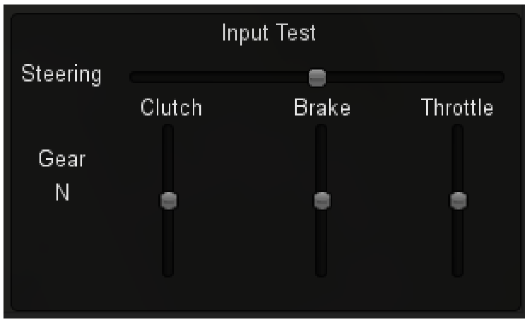

Figure 1. GUI box displaying information about the steering.

Clutch

We implemented the clutch using different rules whenever the value of *Input.GetAxis(Clutch)* changed. The value of the clutch had a range between -1 and 1. The value of the clutch was -1 when it reached the bottom, and had the value 1 when it was untouched.

We made a decision that the clutch would be engaged whenever the value was below -0.4, and this was done by changing the accelerating value called *maxTorque* to zero in a class called *Drivetrain* which contained all the car physics.

We also implemented some specific rules in the *CarController* class to make the engine stop, if the throttle of the car was too low in connection with the gear driven and the speed of the car. In order to make the engine stop *SoundController.engineOn* was set to false, meaning that the sound of the car would be stopped, but also the *FixedUpdate* function in the *Drivetrain* class was stopped since it required the *SoundController.engineOn* value to be true. The *FixedUpdate* function in the *Drivetrain* class, was responsible of making the car move forward and when this function was prevented from running the car stopped accelerating.

Data collection

Logging of the car information was done by using a JSON protocol to encapsulate the data. Information about the time, speed, lateral position (distance to the middle of the road), the values of the steering wheel and pedals and the position in the virtual environment were logged. Furthermore the road was split into different segments, and each segment got a unique number, such that we were able to distinguish between measurements made in the different segments.

The logging of data took place every 500 ms and was written as raw data to a text file.

Driving environment

In order to create the driving environment, a 3D modeling tool was used which enabled us to draw the lines we needed for the road. The tool is called CityScape and it had support for exporting the created environment into Unity 3D.

Another important factor of using CityScape, is that it uses low-polygon models which is not as demanding to represent. This is important since our setup require a large screen resolution, which would create a huge demand on processing power if we did not use low-polygon models. The CityScape tool is shown in figure 2.

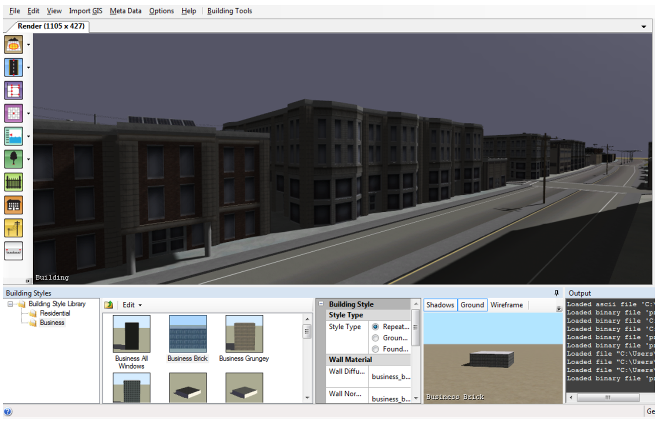

Figure 2. CityScape.

Autonomous vehicles

One of the biggest development challenges, was to add the autonomous vehicles to represent the other cars driving around in the environment. In order to accomplish this task, the cars were given waypoints which they were to navigate by, see figure 3. Each waypoint then had information about the speed limit, and informed the car about the next waypoint whenever the car had reached some predefined radius of the waypoint.

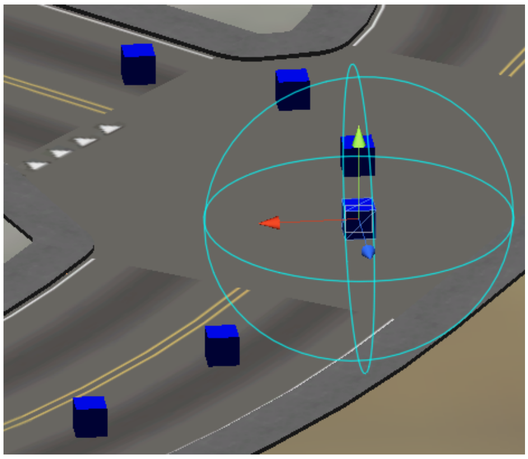

Figure 3. Use of waypoints.

Because more than a single autonomous vehicle was to be driving at the time, the vehicles had to be able to respond to each other. Rules were given to the autonomous vehicles, enabling them to stop whenever a vehicle got to close in front of them or to wait whenever another vehicle were to interrupt the driving path.

Also specific rules concerning traffic lights and crossroads needed to be implemented to the autonomous vehicles when driving in the city. This was accomplished by giving each vehicle the opportunity of seeing whenever a vehicle had to force another vehicle to give way, such that they would not intercept each other. Colliders were used for this purpose on specific parts of the crossroads, which were enabled whenever two vehicles had to be stopped from colliding with each other.

Adding pedestrians

We also added the pedestrians by using waypoints. The models we used were created by Unity Studios and was low-polygon models, which again were needed in order to ensure a better performance when having many pedestrians in the city environment, see figure 4.

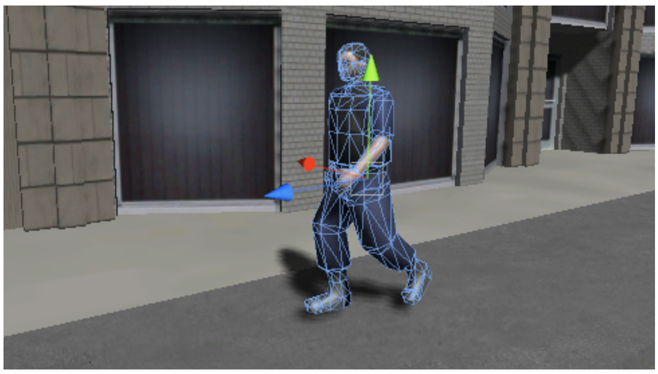

Figure 4. Low-polygon model.

A script called *walk.cs* was implemented, which contained all the important functions to make the pedestrian walk, turn around and navigate towards a waypoint. An animation was linked to the *moveForward()* function, creating motion to the model when walking forward.

When walking towards a waypoint, a gravity function was also implemented in order to calculate the correct position of the pedestrians feet, making sure that the feet was connected to the ground.

Below in listing 1 some of the code used to make the pedestrian move forward is shown.

Listing 1: ***scripts/CharacterControl/Walk.cs*** **- Move forward function.**

```
1   void moveForward ()
2   {
3       charDirection.x = 0;
4       charDirection.y = 0;
5       charDirection.z = walkSpeed;
6
7       charDirection = transform.TransformDirection(
            charDirection);
8       charDirection.y −= gravity ∗ Time.deltaTime;
9
10      characterController.Move(charDirection ∗ (Time.
            deltaTime ∗ walkSpeed));
11      animation.CrossFade("walk");
12  }
```

On line 3-5 a vector describing the direction and speed we want the pedestrian to move is specified. The z-coordinate is describing the front direction of the model, and is therefore set to the *walkSpeed* value specifying the desired speed of the model. The *transform.TransformDirection()* function is then used on the vector, which will transform the vector from describing a models local position, to describing the global position values in the virtual three-dimensional space.

Next the y-coordinate is set by the gravity value, in order to find the correct gradient of the vector direction if the model is moving upward or downward.

On line 10 the model is set in motion by the *characterController.Move()* function, which uses the vector in order to know the correct direction of the movement. On line 11 the model is animated by an animation called *walk*, by specifying the *animation.Crossfade()* function.

Cost and effort

We added 1400 new lines of code during the implementation of the car simulator. Furthermore time was used inside Unity 3D and in CityScape, in order to create the virtual environment. A total development time of 6 man-months was used to implement all the needed functionalities.

The physical components consisting of desktop computer, euro pallets, car seat, monitors, steering wheel, pedals and gear ended up with a total cost approx 2170 USD. The software part ended up costing no more than the time spent, as the used development tools, Unity 3D and CityScape, only were used in their free student versions. If the commercial versions were used a cost of 20500 (Unity 3D Pro: 1500 + CityScape: 19000) USD would had to be added on the software side, and especially the choice of environment tool would had to be reconsidered for a cheaper alternative, e.g. CityEngine.

METHOD

The original goal of the experiment was to find how both static (buildings) and dynamical (autonomous vehicles and pedestrians) objects, influenced the test subjects ability to drive in the simulator and how these objects affected their overall experience of the simulator.

But since the data withdrawn from the software and the eyeglances from the video recordings, showed out not to provide our research with any significant results, the focus was aimed at the problems found in the driving simulator. These problems would be extracted from the qualitative results of interviewing the test subjects after their driving session.

Setting

Our test setup was based on the requirements of building a simulator on a low budget. The simulator itself was placed at Aalborg University, Cassiopeia, and an overview of the setup can be seen on figure 5.

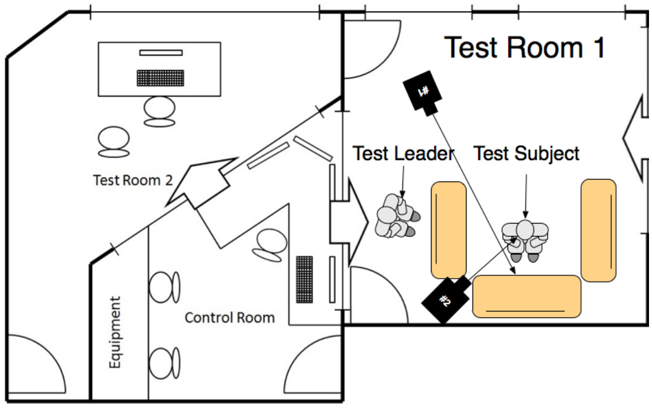

Figure 5. Overview of the lab.

The simulator was build in Test room 1, where both the test leader and the test subject were represented during the test. In Test room 1 we made use of two cameras, one filming how tasks was completed on the iPod Touch, and another camera filming the eyeglances of the test subject. Beyond this the main center screen of the simulator, containing the graphics of the actual driving, was also recorded during the test.

In the control room other persons were placed, one in control of the recording and cameras during the test, and the other occupied with logging what happened and noting any important or unforeseen incident.

Simulator

The construction of the simulator was based on euro pallets as foundation, on which a real car seat was fitted onto in a way such that the seat could be adjusted in terms of distance to the main screen. In front of the test subject was a big flat screen, acting as the main screen on which the straightforward view of the simulator was represented. To both sides of the main screen were two smaller screens, used to give a greater field of view. A picture of the simulator setup can be seen in figure 6. The figure also shows how the steering wheel was mounted directly to the table in front of the main screen. The gear stick was mounted to the right of the test subject, and the pedals were positioned under the front table below the main screen.

Figure 6. Picture of the simulator.

Test subjects

Sixteen test subjects were used for the experiment, which consisted of eight of both genders. The reason why sixteen test subject were chosen, is based on the literature[9, p. 371-373], and to ensure that important test results were not missing from having too few test subjects.

The sixteen test subjects were from 20-25 in age, and were from either scientific, humanistic or social studies.

Procedure

The experiment was started by having the test leader introducing the procedure of the experiment to the test subject. The test subject was then placed in the car seat, and was asked to adjust the seat in terms of distance to the main screen and pedals. First an opportunity of getting to know the simulator and how to control it, was given by letting the test subject do a test run. This was performed in a warm-up scenario where the test subject was driving in a city environment without any traffic.

Tasks

During the test, the test subject was to drive though four different conditions.

These four conditions are shown in figure 7.

Each of these conditions were performed on the same driving track, which is shown on figure 8.

During the first test run, the test leader told the test subjects to maintain the speed at 60 km/h. In the second test run, all

	-	Buildings
-	Highway only	Highway: + Buildings
Pedestrians + Traffic	Highway: + Pedestrians + Traffic	Highway: + Buildings + Pedestrians + Traffic

Figure 7. Overview of the different conditions.

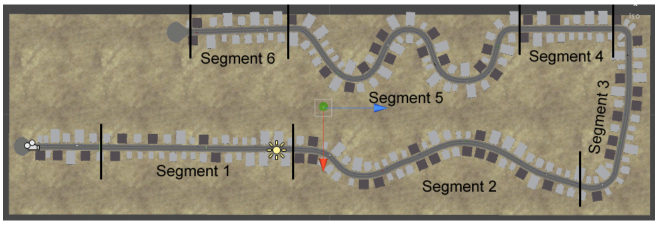

Figure 8. Picture of the driving track.

of the four conditions were performed again, but this time the test subject was to decide the driving speed, without having a speedometer indicating the driving speed. The reason for having these different test runs was to examine if there would be any difference in the results, with variation of the driving speed and having the test subjects driving with the speed they found suitable.

Assignments on an iPod were given every 30 seconds, which the test subject was told only to perform, when feeling that it would not jeopardize their driving safety. The assignments given during the experiment were play/pause, change track, change volume or to tell the name of the song written on the display. Imaginary song titles were used, to ensure that the test subject did not know the titles of the song beforehand.

To ensure that the order of the conditions and assignments was random, a random generator script was made. This script provided the test leader with sixteen documents, describing a random order of the conditions and assignments for each of the test subjects.

Data collection

Three different types of data collections were used during the experiment.

- Data collected within the software (Speed and lateral position).
- Video recordings during the tests (Eyeglances).
- An interview (Answers from test subjects.).

During the test, data was collected within the software of the simulator by logging important information about the positioning of the car and information about the inputs from the steering wheel and pedals. Each test subject was also video recorded during the test, where the overall setup was recorded and a close-up recording of the test subjects eye-glancing.

At the end of each test, the test subject was interviewed by the test leader, answering questions about:

- Personal information.
- Skill level.
- Thoughts about the simulator.
- Thoughts on realism of the simulator.
- Thoughts of how to improve the simulator.

Data analysis

The JSON files containing the data collected within the software was converted in a way that the statistics program, R, was able to handle the data for the subsequent analysis.

The eyeglances were counted and their duration was determined by opening the video recordings in the video editing software, VirtualDub, and use this as a tool to count the exact amount of frames for the duration of the eyeglance. The categorization of eyeglances were performed independently by both of the authors and according to the grouping from [3]. After having registered each eyeglance to one of the three categories the sets from the two authors got tested for agreement with the Kappa coefficient. As the amount of eyeglances for each session were unknown the distribution of them is considered free and for this purpose a *Free-Marginal Kappa* is recommended to use[5]. We used the *Free-Marginal Multirater Kappa* by Randolph[12] to calculate the agreement on each test subject. The highest value for agreement turned out to be κ_{free} = 0,99 and the lowest value to be κ_{free} = 0,74, while the average of all test subjects yielded a value of κ_{free} = 0,88. Based on the average value on κ_{free} = 0,88 the agreement was almost perfect according to Landis and Koch, while the lowest agreement present on κ_{free} = 0,74 still was regarded as a comprehensive agreement[8].

Finally the video recordings were also used in order to transcribe the interviews of all the test subjects. Afterwards statistical analysis was conducted based on the interviews.

Unfortunately, the DVD with one of our male test subjects got damaged and the video of him could for this reason not be used to analyze eyeglances and alongside the answers from the interview got lost. Therefore only 15 test subjects will contribute to this part of the research.

RESULTS

The results in this section will be based on the interview performed on each test subject after the driving test. In the interview the test subjects were asked of issues about how they experienced the simulator and different parts of it, how realistic they felt the driving experience was and which problems and possible improvements they encountered during their drive in the simulator.

The following sections will describe problems that the test subjects had with three aspects of the simulator:

- Sound and graphics.
- Physical setup.
- Realistic driving experience.

Sound and graphics

What do you think about the graphics?

Several of the test subjects said that the graphics suffered from lagging especially when buildings were present. As one of the test subjects said: *"The graphics were nothing to write home about. A very plain world without hills and stuff."* This problem did somewhat affect their driving performance and experience of the simulator in the test, since they had to compensate for the lagging when controlling the car.

A problem was mentioned with the road placed on a very even terrain, which made it hard to determine distances and thereby in time analyze the upcoming curves in terms of how much and when each forthcoming curve was bending. Like a test subject expressed: *"It was hard to see far ahead on the course compared to how radical the curves were. It was difficult to assess how fast you drove and how sharp the upcoming curves was."* And another: *"It is hard to look forward and determine how the curves are in comparison to looking forward on a curve in real driving..."*

What do you think about the sound?

Several mentioned that the engine sound was monotone and not consistent with the gear you were driving in. As a test subject pronounced it: *"You can not really hear the engine when the gear is switched, so when you put it in the fourth gear it does not matter if the clutch is stepped down or not, it just rev up the engine. The sound is hard to relate to."* As consequence of this, the engine of the vehicle in the simulator sounded wrong according to how fast you were driving and how much throttle you were giving.

Others were more in doubt like: *"I think it is pretty well. I felt, however, that you could drive in a completely wrong gear as you wanted to."* And: *"The engine sound was a little crazy. Do not know if it was realistic. It sounded a lot like you did not drive in the right gear, but maybe it was because I did not."* But not all had these rather negative opinions and contradictory one test subject stated: *"The sound was fine enough, I could hear when I switched gears."*

Physical setup

What do you think about the physical setup?

The majority of all the test subjects found the physical setup to be satisfying compared to the setup of a real car. Especially the majority of the test subjects felt the real car seat gave a good feeling of realism to the simulator. The main problem expressed by the test subjects related to the physical setup was the lack of motion in the car seat. This need for motion was expressed like: *"More movement in the seat."* And: *"There could be more vibration when you drive into a car or up on the curb."*

What is your opinion on the steering of the simulator?

To the steering of the simulator, different opinions were given which contradicted a bit. Some said that the steering wheel was very well and had a realistic feeling, like: *"I think it is pretty good. The steering wheel is a little small but otherwise it is good."* And: *"The steering wheel functioned very well. It felt good that there was a little looseness in the steering wheel and that it dragged a little."*

A test subject had some problems with the gear, but was instead quite positive with the pedals: *"The gear shift was difficult to assess. The pedals were fine when you learned the feeling of how much you had to press. The steering wheel also acted very well."*

Others said that they had a few problems with the pedals, which did feel a bit plastic like, and that the gear stick was a bit too small and hard to manage. However the general assumption about the steering was that it was well functioning.

But of course you also have to get used to drive in the simulator, like a test subject mentioned: *"You always have to adjust to a new car."*

Did you use the side windows during the test?

The participators were also asked about their use of the side windows (extra monitors). To this some of the test subjects said that they did not use the side windows at all during the test. Others were somewhat irritated about having them, they claimed that since they never encountered any situations where they had to use the side windows, they would rather not have them, like one test subject said: *"I did not really use them, I think it was confusing when driving in town that you always had something dark in the sidelong glance."*

However some of the participators did mention that maybe the side windows had contributed to the overall impression of the simulator unconsciously, as a test subject expressed it: *"No, it is only the big screen I look at. It is possible that the side screens have influenced me subconsciously."* And another: *"I looked at them to keep track of where I was placed on the road. But I looked most with a sidelong glance."*

Some even said that the side windows gave a greater overview of the road: *"I think you got a very good overview. Even if you do not look directly at the screens you still got the impression."*

Below is the amount of test subjects, who respectively used the side windows, did not use them or was unsure about the matter.

Yes	No	Unsure
4	7	4

Realistic driving experience

How was the feeling of realism during the test compared to a real driving experience?

To the question whether the simulator felt realistic compared to driving a real car, many participators had a hard time explaining how the two things differed. Some of the participators would just describe the simulator as it felt natural or fairly natural, whereas some would give a opposite answer saying that the simulator was very artificial.

However some did give us more comprehensive answers. One said that the simulator compared to a real car was different: *"It felt like something else. Some of the things in the simulator are also present in a real car, you must be very vigilant, you have to adjust, you have to focus, you can not look away because then you end up driving out in one of the sides. In this way some things are similar. But there is some way to go, I think. I had difficulties assessing the speed. You do not get the right feeling of what speed is dangerous to drive with. Because it is a simulator, you do not feel physically moved."* And another explaining differences with driving in curves: *"It felt strange to take a nearly 90-degree turn with 60 km/h, I would normally have taken them with much lower speed. Many things seemed very natural, when driving on straight sections you could sit and relax, but as soon as there came a curve, it was difficult. Because of the sound, I tried as far as possible to avoid shifting gears. It was difficult to assess."*

One of the problems which induced this was that you could not feel the velocity of the simulator, because the simulator was fixed-based and did not move.

Below is the amount of test subjects, who thought they were able to sense the speed of movement in the simulator.

Yes	No	Unsure
4	6	5

What is your opinion on the driving tasks performed during the test?

When asked about if the driving tasks performed on the iPod were disturbing, almost all of the participators felt that they were and had an influence on their driving. Even though the test leader explained to the test subject, only to perform a task on the iPod, when they had the feeling that it would not disturb their driving, several of the test subjects thought they should perform the task right away. Some of the test subject even thought that the tasks were asked when driving in a curve on purpose: *"I tried to do the task right away, as I assumed that is what you wanted me to, since you often asked me to do it in a curve."* Or that they were forced to perform the task even though they felt uncomfortable with the situation: *"I felt that I was forced to perform tasks at times I normally not would have done it. If I drove I would not change song in a curve for instance."*

Some of the test subjects also meant that solving the tasks made them feel stress and raised the feeling of pressure: *"Yes, it disturbed my driving, there were several times where I looked away, and then I immediately had to adjust when I looked up again. I am very unaware of what goes on when I look away."* And: *"Yes, I felt a little bit stressful, you were good to ask just in the curves."*

The general opinion about the software

The test subjects had a lot of mixed comments on the simulator as a whole, from very enthusiastic: *"I think it was really cool, really good!"* To some more critical ones: *"The simulator was fine, but it was hard to estimate how fast you drove."* Or comments on specific parts: *"The steering feels unrealistic by the car's response when turning the steering wheel."*

To the question about their general opinion of the simulator, the results were:

Satisfying	Unsatisfying
7	8

As it can be seen the overall satisfaction was nearly half and half which was in line with the mixed comments of both positive and negative character. The answers to the questions during the interview were likewise nearly distributed evenly and it was possible to find both some positive and negative comments to each area of the simulator covered in the interview.

Main problems from the interviews

The test subjects had with their negative answers, to what they felt was a problem, in terms of comparing the simulator to real life driving, given a comprehensive overview of the problems encountered in the simulator. These problems with the simulator needs to be considered and improved in order to ensure a more realistic and well functioning simulator.

The most reported problems found related to the physical setup was:

- The resistance in the steering wheel did not feel realistic.
- Lack of motion in the car seat.
- The pedals had a plastic-like feeling.
- Many test subjects were unsure about the effect of the side windows.

As it can be seen in the previous sections, there was only a few comments on the physical setup of the simulator, and there was even some disagreement on some of the problems listed. Some participators felt that the side windows was a great feature and others felt that they were completely useless.

The problems to the physical setup definitely have to be considered if the simulator experience were to be improved. But because of the disagreements on each of the problem areas in the physical setup, we would have to examine the effect of each adjustment and improvement of the physical feature more profound.

Below is a list of the problems found related to the software part of the simulator:

- Lagging and bad graphics.
- Plane terrain.
- Implementation of gear shift.
- The sound did not correspond to the driving speed.
- The driver should be seated to the left, instead of in the middle of the car.
- Missing side-and rear-view mirror.
- Implementation of the clutch.

The main problems to the software part were focused on the gear shift, which did not correspond to the correct driving speed and did not sound right. Also the clutch had some problems, where test subjects had a hard time figuring out how to manage it. Another problem was lagging graphics, which would have to be improved by either getting more processing power or creating even more low-polygon models to the simulator.

CONCLUSION

This paper described how a low-cost driving simulator was developed and which challenges and problems it entailed during the progress. This was accomplished by setting up an experiment to investigate test subjects ability to drive in the simulator, and afterwards letting them express their experience with it through an interview.

The results showed that around half of the test subjects was satisfied with the simulator, while the other half thought the simulator at its current state not was satisfiable compared to driving in a real car. With the answers given in the interview, an overview of the necessary improvements had been outlined to get an idea of what needs to be done in each area of the simulator. On the physical side problems with abnormalities in the steering wheel and pedals and the lack of motion in the simulator were present. While on the software side the sound, graphics and better implementation of gear shift and clutch contributed to the list of problems.

The development of the driving simulator showed that it was possible to develop a low-cost driving simulator, in both the time of 6 man-months spent on implementation of software and economically only using physical components of a total cost approx 2170 USD.

The limited realism would always be a question in the development and usage of a simulator and was therefore also a subject of doubt in our research. A way to test the realism would be to compare the simulator against real driving and thereby form a validation of the simulator.

In extension of our research, the problems found in the driving session and subsequent interview would form an overview of where and how improvements should be implemented for the simulator to be useful as a substitution or at least an alternative to testing e.g. an in-vehicle system in a real car.

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Relative validation of a Driving Simulator: Comparing Different Physical Parts

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ABSTRACT
In this study the addition and removal of a number of different physical components were tested for relative validity, also comparing a full simulator setup with a minimal setup, in terms of relative validation. The different components included experiments of testing steering wheel vs. keyboard, BassShakers on/off and sidewindows on/off. Results showed that relative validity was present with some of the depended variables, while others showed quite divergent or even opposite results. This showed that other factors had to be taken into account, e.g. age and experience with driving games.

Author Keywords
Driving simulator, relative validity, validation.

INTRODUCTION
A driving simulator can be used for a number of purposes including initial driver training, realistic simulated driving games and for research purposes in the car industry, to develop prototypes of cars or in-vehicle systems. Using a driving simulator for human factors research, provides a number of advantages over field testing in a real car and a real environment. Among these advantages are the experimental control and the possibility of using a repeatable scenario to isolate the desired variables from exogenous factors which might have an impact on the driving performance[3]. Beyond this a driving simulator provides a cheap and safe method for testing dangerous driving scenarios, which would have been too risky to carry out in a real environment[3, 5].

The problem of using a driving simulator is the validation in terms of realism. The question, "*what is a realistic driving simulator?*", is very hard to answer, since no specific method for testing realism of a driving simulator exists.

However a driving simulator must be sufficiently valid in relation to real driving in terms of driving behavior, in order to relate any of the results from a driving simulator experiment to a real world scenario.[5]

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This article describes the validation of a driving simulator, and evaluates the influence of different physical components on the relative validity of the simulator. The goal was to compare between the addition or absence of physical components to investigate if a more minimalistic edition could be validated towards a full simulator setup.

In the following sections a collection of related work is provided, to give a more comprehensive overview of the term validity and it's use in a driving simulator context. Next a description of the implementation of new features, to the driving simulator used in a previous study are described. Then the method used for setting up the experiment and results found in this context are outlined. Finally the article is finished with a conclusion of the research.

RELATED WORK
To know how simulators are being validated and why this is important, looking at the concepts of validity in a driving simulator would help getting an understanding of this. Furthermore a comprehensive overview of previous studies in the matter, would give knowledge about possible approaches and which parameters would be important in a validation.

Two kinds of validity
Blaauw proposed in 1982 a distinction of simulators validity with the two levels, physical and behavioral. The physical part concerns the simulator's components, layout and dynamics and how these match the physical parts in the real world. Whereas the behavioral part, also known as predictive validity, look at how the human operator behaves in the simulator and the real world respectively.[5]

Physical validity
Physical validity is linked to fidelity, in the way the simulator handles how the vehicle is driven and how it physically reacts to the stimuli presented. Overall the physical validity is the simulator's ability to reproduce all the physical effects present when driving a real vehicle.[5]

Behavioral validity
Even though this physical validity is attractive to obtain, it would only be valuable to human factors research if behavioral validity also can be established. In other words an expensive and more advanced simulator does not necessarily have more behavioral validity than its less expensive and advanced counterpart. For this reason, the behavioral validity

is the most important factor in validating a driving simulator used in human factors research purposes.[5]

Behavioral validity can be described from two aspects, absolute and relative validity. The absolute validity refers to the numerical correspondence between data from a simulated and real environment. Relative validity on the other hand refers to the correspondence between the effects of different variation in the driving situation. This means that the differences between the experimental conditions should be in the same direction and have a similar magnitude on both the simulated and real environment [5]. For a driving simulator to be useful in research and development purposes a sufficient level of relative validity is necessary, because the same or similar effects should be present in the real environment. In contrast absolute validity is normally not a necessity, since research questions mostly deal with the effects of differences between independent variables rather than determining numerical measurements [5].[14]

Validation

Validation asks whether the model and in this case the driving simulator is correct[4]. In terms of a driving simulator, this validation of correctness is compared to real driving as this is what is being simulated. This comparison is of course important to relate any results from the artificial simulator environment to be used in a real environment.

Even though no standard methods for validating a driving simulator exist, a driving simulator has to be validated for a selected driving purpose before it can be considered a valuable research tool.[3]

In the following a collection on validation of driving simulator studies is reviewed and categorized as belonging to Blaauw's physical or behavioral validity.

Physical validation

In [9] a driving simulator based on virtual reality was compared to a desktop, by looking at user-reported presence and measurements on the level of arousal. Under the experiment the user was tested with a high amount of sensory stimulation (virtual reality) and a low amount (desktop) in three different driving conditions. The level of presence was measured by subjective assessments via a questionnaire where the sense of presence, visual realism, and self assessed level of arousal and immersion/concentration were rated. The arousal was collected through physiological signals in terms of heart rate and galvanic skin response during the entire session. The results showed that the presence was rated higher in the virtual reality set up, while there was no difference in arousal.

The aim in [12] was to develop a methodology usable for validating driving simulators with focus on usability of the simulator. The developed methodology was used to validate a truck driving simulator, and data was gathered by the researchers through interviews and observation of the drivers. The results showed the drivers did not have trouble recognizing the different components of the simulator and they felt it was easy to use. Only minor problems with some systems of the simulator were reported.

In the project in [3], a truck driving simulator was developed to be used in driver behavioral studies and in this paper used to study driver drowsiness. To inspect the solving of the challenges related to obtain a realistic replication of driving, an evaluation and validation of the simulator based on subjective assessments from truck drivers was carried out. Lastly after having adjusted and modified the simulator according to the input from the truck drivers, an expert panel was given the task to validate the simulator for drowsiness studies. The simulator received very positive feedback and minor recommendations from the experts resulted in some adjustments implemented in the final version of the simulator.

The above studies including both subjective assessments and expert validation are in the context of Blaauw representing the physical validity of a driving simulator. Because a adequate physical validity was obtained, the driving simulators are considered valid in terms of reacting physically similar in comparison to driving in a real vehicle.

Behavioural validation

To validate a driving simulator, a method used in numerous studies is to compare the driving performance in the simulator with driving performance on real road with equivalent conditions, as close as possible. By comparing results from the different environments it can be determined to what extent the driving simulator match real driving, and to what extent a behavioral validation can be obtained.

In [14] driving behavior was validated in a simulated road tunnel, to find if the correspondence between driving in a real tunnel and a simulated one are sufficient. As driving speed was quite higher and the lateral position deviation was greater in curved sections in the simulated tunnel, the behavioral validity was not satisfactory in terms of absolute validity. But the correspondence showed that the relative validity was good for both speed and lateral position.

The behavioral validation of an advanced driving simulator for its use in evaluating speeding countermeasures was performed in [5]. The participants in the experiment drove on roads which contained transverse rumble strips at three sites, as well as three equivalent control sites. The study showed that participants reacted to the rumble strips, in relation to their deceleration pattern on the control road, in very similar ways in both the instrumented car and simulator experiments, establishing the relative validities. However, participants generally drove faster in the instrumented car than the simulator, resulting in absolute validity not being established.

The objective of [8], was to validate a laboratory-based driving simulator by assessing older drivers driving performance in both the simulator and on real roads. The results showed there was a significant association between the two driving settings. Two-third of the driving performance index in the simulator could be directly explained in the real road driving performance index, after having balanced the results according to age and gender. Thereby the results supported the validity of the simulator and the authors concluded that the simulator was a valid method for a more safe and economical method to assess driving performance for older drivers.

In the study presented in [13], a visual performance test was compared between three driving research environments: Laboratory (low -cost driving simulator with small screen, simple steering wheel and pedals and no audio), Simulator (medium-cost simulator with large screen, rear view mirror screen, real car steering mechanisms and realistic sound system) and Instrumented vehicle (real car). The secondary task (visual performance test) resulted in large effects on the lateral position control in the laboratory setting. Similar effects were found in the simulator and instrumented vehicle setting, but not as pronounced as in the laboratory setting. With these results it was concluded that a low-cost laboratory driving simulator, was capable of being a first-shot testing facility for assessing the impact of an in-vehicle system. For a more detailed assessment of the system a medium-cost simulator was indicated as a serious alternative to driving in a real car and at the same time avoiding the problems and shortcomings with testing in an instrumented vehicle.

The studies above represent a selection of experiments, validating a simulator according to real driving in terms of Blauuw's relative behavioral validation. Because the relative validity is obtained in all of them, the driving simulators are considered useful in research purposes and similar effects are found between the two driving environments.

With a number of studies validating a simulator towards real driving we found it interesting to look in the other direction, and see whether relative validity could be obtained between a fully equipped driving simulator and driving simulator software running on a minimal setup like a laptop. Beyond this it could be interesting to see which components of a simulator could have an influence on relative validation and how the presence of different components would affect the performance and overall experience of the simulator.

To keep the relative validation valid, and to relate the minimal setup or modified simulator to a fully equipped driving simulator, and further on to real driving, looking at the dependent variables used in the comparison between simulator and real driving would be required. In the related studies speed [1, 13, 5, 14, 10, 2] and lateral position [1, 13, 14, 10, 2] showed out to be the most used measurements, and these measurements will because of this form the bedrock of our research.

IMPLEMENTATION

The driving simulator software used in this article, was from a previous article[6]. The simulator was developed in Unity 3D, and consisted of a working representation of driving physics and user control with streering wheel and pedals.

In order to test the relative validity on different components of our simulator, a new testing environment had to be implemented. The testing environment should be able to test the driving speed, lateral position, handling ability and sense of motion. We also wanted to add motion to the driving simulator, to test how this would affect the relative validity. The motion was added by tactile transducers, called BassShakers, which is capable of transforming low bass frequencies into motion. The idea is then to give the BassShakers sound input corresponding to the motion we want to simulate.

We needed to implement the following:

- Technical
  - BassShakers.
  - GameController.
  - Logging system.
  - Car physics.
- Implementation of environment
  - Test track.
  - City environment.

BassShakers

We added BassShakers under the car seat and pedals of the driving simulator. They were then connected to an amplifier, which was connected directly to the audio output of our simulator.

In order to use the BassShakers, new code which could provide low-frequency noises every time we wanted vibrations, was written. We added vibrations to the following situations in the driving simulator:

- When collisions with other objects appeared.
- Based on the RPM of the engine.
- When the clutch was connected.
- Starting and stopping the engine.

The goal with these BassShakers was to add more realism, and examine whether these changes would have any influence on the driving aspects of the simulator. To add this feature changes were made in the *CarController* class, and also a new script called *BassShaker* was created.

The *CarController* class contains all the actions needed to steer the car in the simulator. In this class changes concerning the gearshift and clutch were made, and the *CarController* class was then to contact the *BassShaker* class whenever vibrations were needed.

The *BassShaker* class is controlling the two BassShakers on how to play low-frequency sound that reflected what happened in the driving simulator. To this class a sound clip of 1 second with a 55hz sound was added. Whenever vibrations were needed, we then had to loop this audio clip, and adjusting the volume depending on how large vibrations we wanted.

Listing 1: *scripts/BassShaker.cs* - Change volume.

```
1     if(this.isCollided == false)
2             {
3                 this.volume = 0.4f + (drivetrain.rpm/2)/
                      drivetrain.maxRPM;
4                 // add volume if clutch is connected
5                 if (Input.GetAxis("Clutch") < -0.1f &&
                      Input.GetAxis("Clutch") > -0.7f)
6                     this.volume += 0.5f;
7             }
```

Listing 1 is an example with some code from the *BassShaker* class. The if-statement is executed once every frame, and it ensures that no other collisions with any object has occurred with *this.isCollided == false*. Then *this.volume* is changed based on the current RPM of the engine by using the value *drivetrain.rpm*. On line 6-7 extra volume is added to the BassShakers if the clutch connection point is present, which occurs when *Input.GetAxis(Clutch)* has a value between -0.1 and -0.7.

GameController

The *GameController* has to ensure that all the correct components of the driving simulator is enabled at different scenarios. It was especially important that our *GameController* was able to switch between having different components enabled, since we wanted to focus on testing relative validity on various situations where only some of the features were enabled. The *GameController* was in other words responsible of switching between different test scenarios and different control methods, while it also had to contact all the other scripts involved, such as the *Logger* class.

Logging system

Our logging system needed to be extended because the new test track required that we were able to measure reaction time, lateral positioning, number of traffic cones hit and errors in judging the clutch connection point. As an example, in order to measure the number of traffic cones hit, we had to add a collider on all traffic cones. Each collider had a trigger event which would call a method in our *Logger* class, and log the name of the traffic cone together with the current time. The information would then be encapsulated in JSON format and written to a text file.

Car physics

Since this article is concerned about testing different components of the driving simulator separately, some of the car physics also had to be changed. For example, we had to ensure the same capabilities of acceleration and steering performance whether you were using a keyboard or a steering wheel to control the car. We made changes to the acceleration and braking distance by primarily changing in the *CarController* and *drivetrain* classes.

Test track

Our test track was created in CityScape, where we created a slalom course, a track for testing braking distances, a runway for testing reaction time and a runway for testing our BassShakers.

When the test track was finished in CityScape, we only had all the basics such as asphalt, trees and buildings. The test track was then imported into Unity 3D, where all obstacles such as traffic cones were added. These obstacles were all added together with a collider, adding the capability of knowing when other objects was in contact with the traffic cone. New scripts were also added in order to help logging the test subject's behavior on the test track. A script used to create unexpected obstacles in the form of traffic cones was added to one of the tasks. This script ensured that traffic cones would appear from below the asphalt, whenever the car was getting to a certain distance from the traffic cone position. The current time the traffic cone would appear from the ground was stored in the log, and compared in relation to when the test subject used the brake to show when the obstacle had been detected.

Listing 2: *scripts/CreateObstacle.cs* - Move a cone.

```
if(kegle.transform.position.y <= kegleHeight)
{
    // Get CharacterController object
    CharacterController controller = kegle.
        GetComponent<CharacterController>();
    // Add directional vector
        Vector3 moveDirection = new Vector3(0, 3,
            0);
    // Move the cone
    controller.Move(moveDirection * Time.deltaTime);
}
```

The code in listing 2 is from the *CreateObstacle* class, and is executed when the car is below a specific distance to the traffic cones. The traffic cone is told to move up the y-axis if the y-position is less than the height of the traffic cone (*KegleHeight*). The *CharacterController* object is then found, which contains all the features needed in order to move the traffic cone. The *CharacterController* object is then given a vector which contains only a value of y, which determines that it must move up the y-axis, using the *Move* function.

City environment

Our city environment was also created in CityScape. This environment represented a real city, with autonomous vehicles which were programmed using the scripts from our previous experiment[6]. In addition we created a car which the test subject had to follow in the city environment. A script was connected to this car, creating unexpected stops by using random braking events on the car. A measurement was then made every time a brake event occurs, in order to count the amount of seconds the test subject used to respond to the braking event.

Development time

We added 1227 new lines of code during the implementation of the car simulator in Unity 3D. Furthermore a total of 826 lines of code were written in C#, in order to convert the statistical data from the driving simulator, into something the statistical program R was able to handle. This gave a total of 2053 lines of code, with a development time of 4 man-months used to implement all the needed functionalities.

METHOD

The goal of the experiment was to examine the influence of different physical components of the simulator in terms of their impact on the validity of the simulator. A full simulator setup was compared to a minimal one executed on a laptop and specific components of the setup like the steering mechanism (steering wheel vs. keyboard), vibrations in the car seat (bassshaker on/off) and side windows (side monitors on/off) were compared.

Setting

The test setup was based on the findings from a previous experiment on an earlier version of the simulator[6]. The simulator was placed at Aalborg University, Cassiopeia, and an overview of the setup can be seen on figure 1.

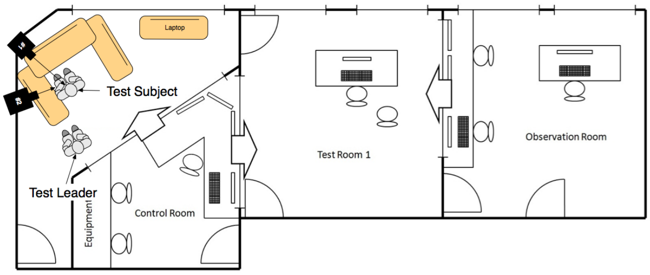

Figure 1. Overview of the lab.

The full simulator setup was build in Test room 2, where the test subject was placed in the driver's seat and the test leader on the left behind the test subject. We made use of two cameras, one filming the test subjects handling of the steering mechanisms, and another camera filming the face of the test subject. Beyond this the main center screen (front window) of the simulator, displaying the graphics of the actual driving, was also recorded during the test.

To the minimal setup a laptop was placed on a separate table with a swivel chair in front of it to the right of the full simulator setup. Again the screen of the simulator was recorded together with a camera filming the test subject and laptop from behind.

In the control room, another group member was placed to be in control of the recording and cameras during the test. Furthermore the person in the control room was via a microphone, able to inform the test leader what to do if any technical problems or unforeseen incidents happened.

Simulator

The construction of the simulator was based on euro pallets as foundation, on which two real car seat was fitted onto to form the interior of a car's cockpit. The seats were mounted in a way such that they could be adjusted in terms of distance to the pedals and steering wheel.

In front of the test subject was a big flat screen, acting as the front window on which the straightforward view of the simulator was represented. In the top of this front window a rearview mirror was represented by software. To both sides of the front screen were two slightly smaller screens to represent the side windows and in the software containing the side mirrors of the car.

To simulate vibrations in the car seat BassShakers were installed underneath the driver's seat and pedals, and was via an amplifier set to vibrate according to the engine, and to vibrate stronger when letting in the clutch or when driving up on a curb.

A picture of the simulator setup can be seen in figure 2. The figure also showed how the steering wheel was mounted directly to the table in front of the center screen, and when the keyboard was used as the steering mechanism, it was located the same place and the steering wheel was removed meanwhile. The gear stick was mounted to the right of the test subject, and the pedals were positioned under the front table below the center screen.

Figure 2. Picture of the full simulator setup.

Besides the full simulator setup a minimal setup with a laptop running the software was also set up, see figure 3.

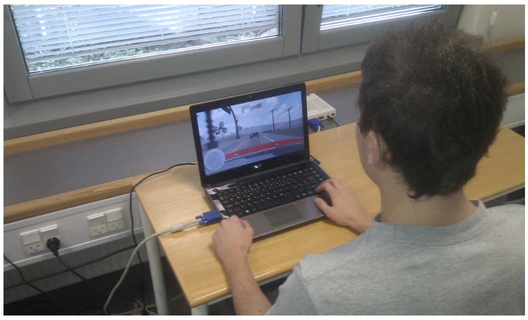

Figure 3. Picture of the minimal simulator setup.

Test subjects

Sixteen test subjects were used for the experiment, which consisted of eight of both genders. Furthermore we grouped the test subjects in age groups with 8 young (19-25) and 8 old (37-58). So there were 4 young females (average age 21,75), 4 old females (average age 52,25), 4 young males (average age 22,5) and 4 old males (average age 46,5). These groups were chosen, because we by this were able to investigate not only differences between sexes, but also differences related to age.

The test subjects were from a wide range of professions and studies and the selection of them were instead based on the fact that they were holding a driving license and was driving frequently.

The reason why a total of sixteen test subject were chosen, is based on the literature[7, p. 371-373], and to ensure that important test results were not missing from having too few test subjects.

Procedure

The experiment was started by having the test leader introduce the procedure of the experiment to the test subject. The test subject was then placed in the car seat, and was asked to adjust the seat in terms of distance to the steering wheel and pedals.

First an opportunity of getting comfortable with the simulator and how to control it was given by letting the test subject do a test run. This was performed in a warm-up scenario starting randomly with either steering wheel or keyboard where the test subject was driving in a city environment without any traffic. This scenario was after the first run repeated with the other form of steering to let the test subject get used to both the steering wheel and keyboard.

Tasks

During the test, the test subject was to drive though four different experiments testing the effects of a specific physical component of the simulator or as in the last experiment testing the full setup against the minimal one.

Experiment 1 - Steering wheel and pedals vs. keyboard

The test subject started with the steering method last used in the warm up scenario, and after three tasks, the steering method was switched back to the method first used in the warm up. The three tasks were as follows:

Task 1 - Slalom course: In this task the test subject was told to slalom between a series of cones to investigate their ability of steering in the simulator. A white line guided on which side they were supposed to pass the cone and they were told to be as close to the cone as possible without hitting it. In the first run they were told to hold the speed at 40 km/h, and in the second run, without speedometer, they were told to drive through the track as fast as possible but still with the focus of performing the slalom correct and not hitting the cones.

Task 2 - Braking distance track: The ability to brake and the assessment of the braking distance was the focus of this task. The test subject was told to approach a series of cones at respectively 50, 80 and 110 km/h, and slam on the brakes in order to stop as close as possible to the upcoming cones.

Task 3 - Runaway with moving obstacles: In the last task in this experiment the reaction time and the ability to brake and steer past upcoming hurdles were tested. The test subject should drive forward, until a cone would appear from the surface, and as soon as this happened, they were to brake and change to the opposite lane. In the first run the test subject was told to get the speed up on and maintain it at 60 km/h after having changed lane. In the second run, without speedometer, the test subject was instead told to drive through the track as fast as possible but still with focus on keeping the lane and not hitting the cones.

The order of these three tasks were randomized between subjects both when steering with steering wheel and keyboard.

Experiment 2 - BassShakers on/off

The BassShakers were tested in this experiment and half of the test subjects started with them on and the other half off and opposite in the next run. The effect of the BassShakers were tested by having the test subject starting and stopping at some white lines on a road on curved terrain. After having stopped by the white line the task was to get the car going again and stop and repeat this by the next white line. In this manner the experiment would investigate if the test subjects did better at letting in the clutch and getting the car going when the BassShakers were turned on.

Experiment 3 - Side screens on/off

In this experiment it was tested whether having the side windows in the simulator helped the test subjects in assessing the speed they were driving. Half of the test subjects started with the side screens active and the other half with them turned off and opposite in the next run. Driving without speedometer on a circular road with only oncoming traffic the test subject was told to drive at either 60, 80 or 100 km/h in a random order. When the test subject felt they drove with the speed they was supposed to, they announced it to the test leader who registered the exact time by hitting a button. The current speed was then to be hold in 20 seconds, before the test leader gave a new speed to reach.

Experiment 4 - Full simulator setup vs. minimal setup

In the last experiment the full simulator setup, see figure 2, was tested up against the minimal setup with only the software and a laptop, see figure 3. Half of the test subjects started at the full simulator setup and then moved on to the minimal setup and vice versa for the other half. The experiment was set up to investigate the differences between our simulator, and an absolute minimum of physical setup, in terms of a number of measures and in the overall experience the test subjects had with the two different settings.

The test subject drove a preset route by following a car driving in front of them. The car in front putted on the brakes at random times, and as soon as the braking lights lit up, the test subject should mark this by pressing their own brake. The test subject was told the speed was not important, and that they only had to concentrate on following the car and roadway and break whenever the car in front braked.

Data collection

During the test, data was collected within the software of the simulator by logging important information about speed, lateral position, time (reaction time, track completion time), values of steering wheel and pedals, distance to cones (experiment 1) and cars (experiment 4), collisions with cones (experiment 1) and cars (experiment 4) and the engine stalls (experiment 2).

Each test subject was also video recorded during the test, where the focus was on facial expressions, verbal expressions, handling of steering mechanisms and simulator software (front window).

At the end of each test, the test subject was interviewed by the test leader, answering questions about personal information, physical setup, simulator software, simulator sickness and how to improve the simulator.

Data analysis

The JSON files containing the data collected within the software were converted in a way such that the statistics program, R, was able to handle the data for the subsequent analysis.

The video recordings was primarily used as backup to support the finding or negation of abnormalities in the data collected within the software. By looking at the video recorded of the simulator software the reason of divergent results could be found. These could be further supported by seeing how the steering was handled or which verbal and facial expressions the test subject showed in the concerned situation.

Finally the video recordings were also used in order to transcribe the interviews of all the test subjects. Afterwards statistic analysis was conducted based on the interviews.

RESULTS

This section contains the results from our experiment dealing with relative validation. Our results are mainly based on data collected from our driving simulator during the experiment. Subjective evaluations of the simulator based on an interview of the test subjects will be further examined in the discussion.

Our results will be divided into the following sections:

- Experiment 1 - Steering wheel and pedals vs. keyboard.
- Experiment 2 - BassShakers on/off.
- Experiment 3 - Side windows on/off.
- Experiment 4 - Full simulator setup vs. minimal setup.

Experiment 1 - Steering wheel and pedals vs. keyboard

This experiment consisted of three different tasks, where the focus was on the ability to control the driving simulator using the steering wheel and pedals vs. using the keyboard. The results were divided in relation to average lateral deviation (distance to the middle of lane), number of collisions with cones, reaction time, distance to cones and execution time.

The average lateral deviation

The average lateral deviation was measured both on a slalom course and a runway with moving obstacles. Results showed that there was a significantly greater average deviation among the old compared to the young test subjects, with an average deviation of both runways at 2.33 meters for the young and 3.03 meters for the old, task 1: ($F = 4.52$, $p = 0.0063$) and task 3: ($F = 5.25$, $p = 0.0152$).

Looking at the deviation using the keyboard in relation to the steering wheel and pedals, it showed no significant difference at the slalom course ($F = 0.11$, $p = 0.95$), whereas there was a significant deviation at the track with obstacles ($F = 7.92$, $p = 0.0002$) where using the keyboard gave a larger deviation than using the steering wheel of 0.42 meters. The results of lateral deviation for task 1 (slalom course) and task 3 (obstacles) is shown in figure 4, where especially the maximum lateral deviation was found to be much larger with keyboard in task 3.

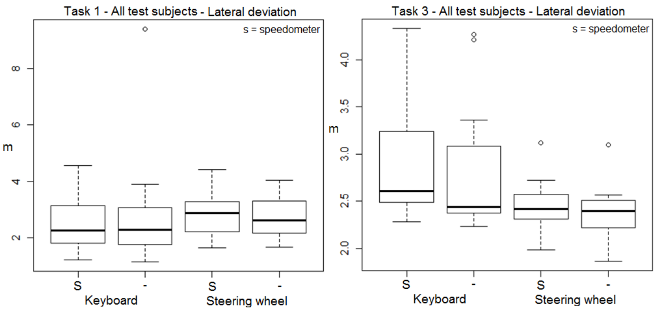

Figure 4. Lateral deviation.

Our result in task 3 was an indication of a difference in lateral deviation when there is a need for emergency avoidance because of upcoming obstacles. The difference was however smaller when you needed to avoid them and the obstacles were known in advance as in task 1, where the significance was 0.95, meaning that there was almost no difference between using a keyboard or steering wheel. The lateral deviation can therefore be said to depend on the test scenario. This means that in relation to the lateral deviation, it would be suifficient to use a keyboard if there were no unforeseen obstacles where you would need to make drastic maneuvers, as there was in task 1.

Generally there was a tendency for the old to have a much greater lateral deviation than the young. If isolated from each other, the old had an average difference in deviation of 0.71 meters ($F = 7.68$, $p = 0.0012$) significant between the keyboard and steering wheel, whereas the difference was only 0.13 meters for the young ($F = 2.60$, $p = 0.0793$) and was not significant. Both groups had a larger deviation with keyboard, but among the results for the young, it indicated that the lateral deviation did not have much influence on whether they used a keyboard or a steering wheel.

Number of cones hit

Looking at the number of cones hit in task 1 and task 3, we got two significant results, seen in figure 5.

As can be seen in figure 5, using the keyboard gives significantly more cones hit than using a steering wheel. In both cases there was significance, task 1: ($F = 3.99$, $p = 0.0117$) and task 3: ($F = 6.60$, $p = 0.0009$). This result gave in relation to lateral deviation, a different picture on whether to use a keyboard or a steering wheel, since even though the difference in lateral deviation was very small in task 1, the number of cones hit with the keyboard in task 1 was significantly larger.

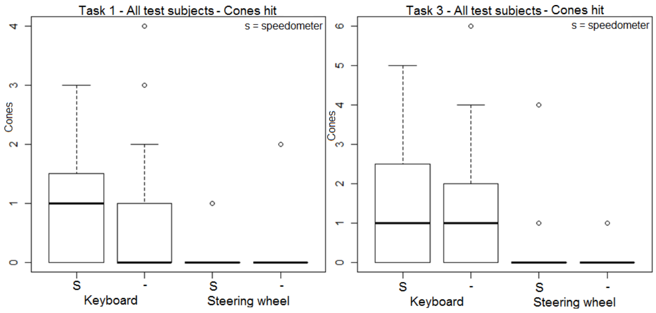

Figure 5. Cones hit.

Looking at the results in relation to the age groups, there was a tendency for the old to have more collisions with cones than the young (F = 2.89, p = 0.0427) which is significant.

Reaction time

The reaction time was measured by the time it took the test subject to respond to obstacles in task 3. The reaction time between keyboard and steering wheel (F = 0.92, p = 0.4372) was not significant, and the reason for this was that the two age groups had opposite results in reaction times for keyboard and steering wheel. The old had a longer reaction time overall than the young had (F = 5.64, p = 0.0018), which may refer to that this type of task was more attention demanding for the old test subjects.

Below are the reaction time results for both the young and old test subjects:

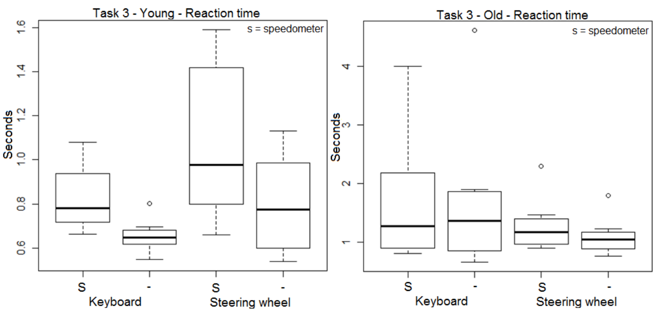

Figure 6. Reaction time.

When the reaction time of the two age groups were separated as in figure 6, it turned out that the young had a significantly lower average reaction time of 0.2 seconds on the keyboard (F = 6.44, p = 0.0029). The opposite was true with the old, which have a higher average reaction time with the keyboard of 0.49, the result was however not significant (F = 1.33, p = 0.29).

Sense of distance

When looking at the test subjects judgment of distance it turned out that there was significance in, when using steering wheels and pedals, the test subject would stop 17.97 meters sooner than with keyboard (F = 2.50, p = 0.0364). This applied to all three different speed limits, where the average distance to the cones with keyboard was 27 meters, and 44.97 meters with steering wheel. This difference may be due to the test subjects feeling a greater urge to not hit the cones when using the steering wheel and pedals, because this steering method felt more realistic.

Execution time

In relation to execution time we had significant results indicating that the old had a longer execution time than the young test subjects in task 1 (F = 8.64, p = 0.0007) and task 3 (F = 7.06, p = 0.0004). When looking at the results between steering methods, we got no significance of the results, task 1: (F = 1.92, p = 0.1361) and task 3: (F = 2.04, p = 0.1222). The reason for this was that the two age groups had opposite results, where the young had a larger execution time with steering wheel, and the old had a larger execution time with keyboard.

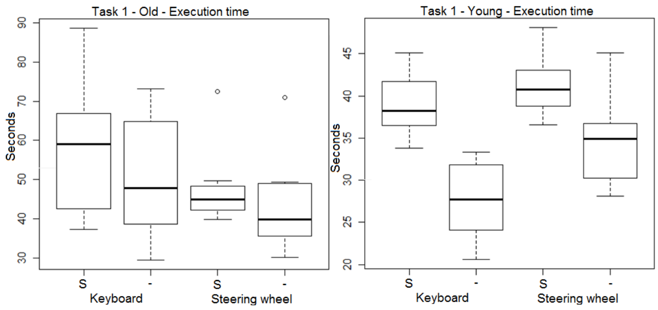

Figure 7. Execution time.

Both results on figure 7 were significant. On the result for the old, it can be seen that they had a significantly longer average execution time using keyboard (F = 3.55, p = 0.032), with a longer execution time of 8,45 seconds on average. The young had a significantly longer execution time using steering wheel (F = 21.81, p = 0.0001), with a longer execution time of 4,6 seconds on average. Especially for the young, it was easy to see that they performed much faster when they are allowed to drive without the speedometer, which was not nearly as distinct with the old.

These results showed that the old clearly had benefited from using the steering wheel and pedals instead of the keyboard, while the young were doing well with both of the steering options.

Experiment 2 - BassShakers on /off

In experiment 2 we tested whether it made a difference with the number of errors using the clutch, if the test subject had vibrations from BassShakers. None of our results proved to be significant, from which we can conclude that the BassShakers do not affect the use of the clutch.

Experiment 3 - Side windows on/off

The goal of experiment 3 was to examine whether there were differences in the sense of driving speed when side windows were enabled. Here, none of the results were significant, but in situations where the test subjects were to drive at a speed of 60 km/h and 80 km/h, there was a tendency towards a higher deviation of speed without the use of side windows. This could possibly indicate that it was harder to measure speed without the side windows, but it cannot be concluded since the results were not significant.

If we look at the driving speed in general, the results all had in common that the test subjects drove much faster than they were asked to do. This indicated that the test subject generally had a very hard time judging the driving speed in the simulator. When asked to drive 60 km/h their speed was on average 75 km/h, the same goes for 80 km/h = 95,45 km/h and 100 km/h = 113,7 km/h on average.

Experiment 4 - Full simulator setup vs. minimal

The goal of experiment 4 was to investigate the difference in having a full simulator setup compared to the minimal setup with a laptop. When looking at the results, it again appeared that the old had a significantly larger lateral deviation ($F = 11.94$, $p = 0.0008$) and significantly longer reaction time ($F = 3.93$, $p = 0.0186$) than the young test subjects.

The lateral deviation ($F = 5.17$, $p = 0.0381$) was significantly larger on the driving simulator than on the laptop. The reaction time also had a larger average time on the driving simulator, but this result was not significant since the laptop had a much larger deviation of the reaction time ($F = 0.37$, $p = 0.5537$). The reason for this was that the reaction time on the laptop among the old was larger than on the simulator ($F = 3.89$, $p = 0.0890$), whereas the opposite was the fact with the young with a significantly smaller reaction time on the laptop ($F = 17.89$, $p = 0.0039$). The reason for less lateral deviation on the laptop may be because it was much easier for the young to maintain a straight line while driving with keyboard, because you only had to push the forward key.

The amount of collisions with the car in front of the test subject can be seen below:

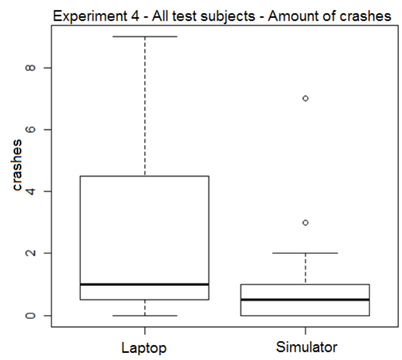

Figure 8. Amount of crashes.

On figure 8 there was significantly more collisions with the car on the laptop ($F = 9.93$, $p = 0.0066$). This result may be due to the fact that our test subjects did not have a feeling of realism on the laptop, and therefore did not concentrate as much on not hitting the car in front. Another reason could be that it was simply much harder to control the driving speed on the laptop's keyboard.

DISCUSSION

This discussion will be based on the results, together with the interviews from our experiment.

Comparing interviews and results

Our results indicated that the old test subjects generally performed worse than the young test subjects in our experiments, no matter whether it was in our driving simulator or on the laptop. This can be explained by the old test subjects generally having less resources in relation to attention demanding tasks[11]. Another reason was that the old test subjects had less experience with video games which connects to controlling a driving simulator or laptop. Looking at our interviews, it turned out that the majority of the old test subjects had almost no experience with video games, while the young had much more experience in this category.

Most of the young test subjects was used to video games with a keyboard, which also was shown in our results, where the young test subjects in most cases got the best results when using a keyboard rather than steering wheel and pedals. However the old test subjects generally performed best with a steering wheel, and this showed the importance of having a variety of age groups when testing, because with only young test subjects we would not have found nearly as many problems with the different components of our simulator.

If we look at our interviews, it turned out that all the test subjects agreed that the full simulator setup was necessary to create a realistic scenario. All the old test subjects preferred to use the steering wheel and pedals, whereas a few of the young test subjects preferred using the keyboard.

Almost all test subjects said that the BassShakers and side windows not had any particular impact on their driving, but gave some minor benefits in terms of realism. This was also shown in our results, where both the BassShakers and side windows did not provide any significant findings.

Validation

When looking at relative validity of a driving simulator, previous articles had mainly been concerned with relative validity in relation to speed and lateral deviation. Looking at our results in relation to lateral deviation, we did not find any significant differences of lateral deviation in some of the test scenarios, meaning that there was grounds for saying that relative validity of lateral deviation exist in the test scenarios, e.g. task 1. The same was applied to the driving speed, where no significant differences was found. But when looking at our other measurements, being the number of cones hit, reaction time and execution time, we got significant results indicating that there still was a big difference between using keyboard and steering wheel, and also between the minimal and full simulator setup.

Looking at the number of cones hit in task 1, where the lateral deviation was not significant, it turned out that all test subjects hit significantly more cones with keyboard than with the steering wheel. The reaction time and execution time, also showed results indicating that young test subjects managed the keyboard best, whereas the old test subjects managed the steering wheel best. These results showed how important it was to look at other measurements than lateral deviation and speed, since other measurements may point in other directions as our results had proven.

Our test of the full simulator setup compared to the minimal setup with the laptop, showed that there was a larger average lateral deviation and average reaction time on the driving simulator than on the laptop. These differences was not particularly large, and when looking at the old test subjects separately, it turned out that they had a larger average lateral deviation and average reaction time on the laptop. The reason why the laptop got the best results overall, was that the young test subjects managed the laptop much better, possibly because of their experience with driving games on a computer. But when looking at the amount of crashes, it turned out that all age groups performed significantly worse on the laptop, which may refer to the test subject was having a harder time judging the distance on a laptop to avoid collisions.

CONCLUSION

In this article we implemented different testing features to a driving simulator developed in Unity 3D. This was done in order to test relative validity on the different physical components of a driving simulator.

The simulator was tested by a lab-based experiment with sixteen test subjects, and the test focused on measuring the lateral deviation, driving speed, reaction time, braking distance, amount of cones hit and amount of crashes.

We found relative validity of lateral deviation between the keyboard and steering wheel in task 1, which was a test scenario with a slalom course. This indicated that their performance in terms of holding a correct lane when using either keyboard or steering wheel was the same in that specific test scenario (task 1). Another relative valid result was between the use of side windows or use of BassShakers, in which case none of the two components had any influence on the driving performance. More relative valid results were found, but a shared tendency of all the relative valid results was that they only involved a single test scenario, age group or dependent variable.

A relative valid result of one dependent variable(e. g. lateral deviation of task 1), did not necessarily comply to the other dependent variables, meaning that a relative valid result of lateral deviation not always ensured a relative validity of the driving speed, reaction time etc. This means that you have to ensure relative validity of all the dependent variables you need to test, in order to be sure that relative validity exist between the physical components of the simulator.

Another important observation was that relative validity of a measurement often only was related to a single scenario. In our results we found that lateral deviation was relative valid between keyboard and steering wheel in a slalom course, whereas we did not find the same relative validity in another scenario with moving obstacles. This indicate that relative validity of a simulator also depend on the type of scenarios.

Relative validity was also dependent on the age group, since different age groups had diversity in the results based on their experience with driving games and attentional resources.

A limitation of this research is that we have not compared all the different test scenarios possible in a driving simulator. There are still a lot of physical component setups which could be tested for relative validity, like the impact of having a larger screen instead of a small one, the position of different components etc.

Future work would be to test whether two setups of a driving simulator both would be relative valid to real driving, and if both setups at the same time was found to be relative valid to each other in a lab experiment.

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