Determining the Importance of Real-Time Visual Information for the Remote Supervision of an Autonomous Agricultural Machine

by

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Abstract

Researchers worldwide have invested effort into the design of autonomous agricultural machines to make them more capable, robust, and safe. The topic of control interface design receives much less attention. The current level of agricultural machines automation can be called ‘supervised autonomy’, which means that the human is not removed from the human-machine system but has to perform a supervisory role. In this study, the importance of live video for remote supervision of autonomous agricultural machine was investigated. The study was conducted using a simulation of an autonomous agricultural machine control interface. Results of the study showed that live video footage is less important for the supervisory task than information provided by indicators. At the end of the experimental session the participants spent about 70% of time monitoring indicators. The participants noted that they would like to be able to get live video either all the time or on demand.

Acknowledgments

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1 Introduction

The idea of an autonomous agricultural machine is not new. The first attempts to make a driverless tractor happened in the early 1940s. Frank W. Andrew made a tractor run circles around a fixed wheel by connecting a wire to the steering arm (Condon and Windsor 1940). Later research focused mainly on automatic steering systems (Pedersen et al. 2006; Wilson 2000). In the last twenty years, new technologies, such as RTK GPS, computer vision, guiding sensors, and a general increase of computing power, have enabled the development of automation technologies for different agricultural tasks (Billingsley et al. 2008). One of the first prototypes of an autonomous tractor was presented by John Deere in 2008 (Murray 2008). After more than two decades of research the company recognized that to create a truly autonomous machine they had to replicate everything that a farmer sees, hears, and senses tactilely in the form of machine sensors (Gershgorn 2017). The new John Deere S700 combine has the latest technologies for optimization and automation of harvesting, however, the operator is provided with camera images of the process to make sure that everything is working correctly (John Deere 2017).

Some researchers see the future of agricultural machines in the modification of existing machines or building the same size autonomous machines (Bechar and Vigneault 2016). Others think that it is more effective to run coordinated groups of small robots (Barrientos et al. 2011; Blackmore et al. 2002b; Blender et al. 2016; Emmi et al. 2014). In any case, autonomous agricultural machines do not exclude a human in a human-machine system. It would change the role of the operator from direct control to supervision. Development of autonomous machines is only one part of the problem; creation of a convenient interface for the supervisor is another key problem to overcome (Endsley 2017).

2 Literature Review

2.1 Automation and agricultural machines

2.1.1 Automation of agricultural tasks

The general idea that comes to mind when the word ‘automation’ is used is that a machine replaces a human and performs the task both faster and better (Salvendy 2012). A more realistic view of task automation is that while most autonomous systems can perform actions alone they require human supervision (Endsley 2017). The ideal automation strategy should account for the dynamics of the human-machine system and must consider humans and machines as a system rather than incompatible components that somehow have to work together (Sandom and Harvey 2009). A task can easily reach a high level of automation if there are existing technologies for automation and the influence of random factors is minimized by controlling the environment (Lehto and Landry 2012).

In the agricultural domain, automation of the processes faces uncertainties related to the real-world environment (i.e. crop variability, uneven ground, weather changes, fog, dust, sudden appearance of people or animals) (Conesa-Muñoz et al. 2015). The influence of these uncertainties can be minimized using one of the three strategies: 1) careful engineering, 2) reasoning, and 3) tolerating the uncertainty (Saffiotti 1998). The careful engineering approach assumes advancement of the robot and changes to the workspace to remove uncertainty. The approach works well for industrial robots, but has limited application for agricultural robots. The robot advancement might drastically increase its cost and fragility. The engineering of the workspace is usually undesirable and/or impossible and in most cases is too expensive. The reasoning approach assumes planning of actions based on the model of the environment that was obtained using sensors. This approach has some drawbacks. First, the model is always incomplete and inexact due to limitations of sensors and software. Second, the dynamic environment likely makes the model out of date fairly quickly. The tolerating approach assumes that the robot has a system that controls execution of a primary task and can monitor, estimate effects, and react to problems (Conesa-Muñoz et al. 2015). If the system cannot overcome the problem, information is reported to the supervisor in charge. Due to the wide diversity of agricultural tasks, the automation of agricultural machines involves all three approaches in different proportions.

2.1.2 Advances in the development of autonomous agricultural machines

Major agricultural equipment manufacturers presented their concepts of autonomous machines (Bechar and Vigneault 2016; John Deere 2017; New Holland 2016). Other companies offer modifications of existing tractors to autonomy (Demarest 2015; Emmi et al. 2014).

A project of automation of routine operations in orchards, such as mowing and spraying, (Moorehead et al. 2009) showed that it is possible to improve productivity by replacing multiple tractor operators with one supervisor who monitors several semi-autonomous tractors. Testing of that system resulted significant improvement of productivity, about 30%, over the conventional (manual) method of tractor control (Moorehead et al. 2012). Factors that ensure productivity improvement are better path planning, constant working speed, lack of breaks, and elimination of tractor backing up. However, the system requires a human supervisor for task assignment and solving problems that automation cannot overcome.

In 2016, CNH Industrial (New Holland) introduced its concept of an autonomous tractor (New Holland 2016). The tractor is a transitional link between traditional and fully autonomous tractors. It can perform tasks in autonomous mode or in tandem with other machines and work under manual control as it is equipped with a standard cab (Figure 1). The tractor can be controlled and monitored via a portable tablet or a desktop computer. The tractor autonomy was described as supervised automation. The tractor is equipped with sensors and can detect obstacles, however, the decision of how to avoid or bypass the obstacle is made by the supervisor.

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Figure 1. T8 Blue Power tractor, concept autonomous tractor by The New Holland (newholland.com)

In 2017, researchers from the United Kingdom conducted an experiment called "Hands Free Hectare" (Hands Free Hectare 2017). The project claimed to be the first in the world to farm a crop with only autonomous agricultural machines and drones. The team believes that the usage of smaller and lighter machines than the common ones improves soil health and is better suited for precision agriculture practices. Seeding and spraying was carried out by the Iseki tractor equipped with a precision sprayer and vineyard drill. The harvest was carried out by a Sampo harvester designed to harvest trial plots and modified to act autonomously. The aim of the project was to prove that all the technologies needed to farm crops with autonomous machines have been developed. It was confirmed with a successful harvest of spring barley in September 2017.

Autonomous agricultural vehicles still have issues with safety and reliability (Lyon 2017). Usually agricultural machinery is big, heavy, and mobile which, in case of unsupervised work, may be very dangerous if safety systems failed (Conesa-Muñoz et al. 2015). Technologies that ensure autonomy of the agricultural machines, such as RTK-GPS, auto steer, auto turns, laser and RGB sensors, machine vision, and computational methods, have been developed by major manufacturers (Li et al. 2009; Lyon 2017). These technologies ensure that a tractor can follow a predefined path in autonomous mode but there is no practical application until it can react and/or avoid unknown obstacles (Blackmore et al. 2004). Autonomous and semi-autonomous agricultural machines still require a human to supervise the work process and solve problems that the machine cannot overcome (Endsley 2017).

2.2 Supervisory task and live video

In human-robot interaction, the human can assume three different roles: supervisor, operator, and peer (Scholtz 2002). The supervision of autonomous agricultural machines is related to “human supervisory control of robots in the performance of routine tasks” (Sheridan 2016). That type of control assumes that a robot has capability to sense its environment and perform a limited set of actions defined by the software. The supervisor monitors the implementation of the tasks and can step in to modify plans and goals and solve problems that the software cannot overcome (Scholtz 2003). The operator role includes software modifications and testing of hardware modifications to make sure that the robot behavior is acceptable. The peer role involves dialog with the robot by giving commands to correct or direct the robot within a global goal. The peer role does not assume changes to the global goal (Scholtz 2003).

In the case of robot teleoperation during urban search and rescue operations, an operator relies heavily on live video over other information on the screen (Baker et al. 2004). However, when the supervisors were using only video (rather that sensors), they had problems with navigation and exploration (Casper and Murphy 2003). Analysis of typical control interfaces of a single robot showed that the interface include a camera view, map, and various types of information from sensors (Yanco et al. 2004). Each piece of information was provided in a separate window. Future improvements of the interface included 1) augmentation of a camera view with a map and 3D computer graphic and 2) camera centered approach with the camera view is located in the center of the screen and other information surrounding it (Cross II and Gilbert 2008). All these designs are based on the idea that the robot requires full time control and the primary source of information for the supervisor is the camera image.

Agricultural tasks are much more structured and consistent than rescue operations. Agricultural robots perform routine tasks and, under normal conditions, do not require the full attention of the supervisor (Bechar and Vigneault 2016). The importance of live video for supervision of autonomous agricultural machines is unknown. Blackmore et al. (2002a) suggested including live video from on-board cameras in a control interface for a better understanding of the tractor’s environment. The CNH Industrial autonomous tractor control interface includes images from four cameras mounted on the tractor (New Holland 2016). At the same time, other authors designed and tested user interfaces based on computer graphics without adding live video streams (Johnson et al. 2009; Moorehead et al. 2009). Research is required to identify the importance and the necessity of integration of camera image(s) into an autonomous agricultural machine control interface.

2.3 Techniques for assessing performance of Human-Autonomy systems

Human factors studies involve several techniques to evaluate the influence of factors on human performance. The most common indicators are situation awareness (SA), mental workload, and fatigue (Lehto and Landry 2012; Salvendy 2012). Situation awareness is a well-developed concept that is often used in studies that assess new interface designs (Endsley et al. 2003). The situation awareness construct was selected as an indicator of human performance for the study and is described in detail in the following sections.

2.3.1 Definition of situation awareness

Situation Awareness (SA) is defined as an understanding of what is going on (Endsley 2000). There are numerous theories of SA, but the three-level model proposed by Endsley (1995) is the most commonly used model of SA (Salmon et al. 2009).

Endsley (1995) defines SA as 'the perception of the elements in the environment within a span of time and space, the comprehension of their meaning, and the projection of their status in the near future'. Situation awareness is critical for effective decision making and actions. Often information can be classified as either important or irrelevant in terms of a particular job or task. The relevance to the task information is only important for SA. How the person perceives the information defines the level of SA that is achieved.

Level 1 SA is achieved when an operator perceives necessary information to perform the task (Endsley et al. 2003). Obviously, different tasks require different types of information to maintain situation awareness. The operator typically uses a combination of visual, auditory, tactile, taste, or olfactory senses to perceive information (Endsley and Garland 2000). For example, an operator of an agricultural machine sees navigation clues and indicators on a visual display, feels vibration and force feedback of the wheel, hears engine sounds and other mechanisms. Problems with achieving level 1 SA may happen if the user of the system has to perceive too much information at the time or key information has not been detected because the user was distracted or had to deal with other information to complete other tasks. Thus, a critical part of level 1 SA achievement is to ensure that necessary information is presented and the user easily perceives it.

Achieving level 2 SA means that the operator understands the meaning of perceived information in relation to relevant goals (Endsley et al. 2003). The operator has to process the data, integrate pieces of information, and forms an understanding of information that is important for achieving the present goals. Forming level 2 SA is a demanding process and requires good knowledge of the system, tasks and requirements. Problems with achieving level 2 SA may happen if the user cannot correctly understand the meaning of information or the user does not have experience with a particular task.

Achieving level 3 SA means that the operator perceives information, understands its meaning in relation to relevant goals, and has the ability to predict how the situation will develop (Endsley et al. 2003). The operator must have a very good understanding of the current situation and how the system works to achieve level 3 SA. Projection ahead allows the operator to be proactive, avoid undesirable situations and quickly respond to emergencies. An operator may have problems with achieving level 3 SA in case of insufficient knowledge of the system or because of mental overload caused by information processing. Poor system design and lack of experience create significant difficulties in obtaining Level 1 and Level 2 SA and an operator may never reach level 3 SA.

2.3.2 Situation awareness measures

The three level model is the most common model of SA and the majority of SA measurement techniques are based on this model (Salmon et al. 2006). There are multiple approaches to SA measurement, which can be separated into the following types: freeze probe recall techniques, real-time probe techniques, post-trial subjective rating techniques, observer rating techniques and process indices (Salmon et al. 2009).

Freeze probe recall techniques involve direct SA measurement during ‘freezes’ in a simulation of the task (Salmon et al. 2006). Typically, a task simulation is ‘frozen’ at a random moment, monitors are blanked, and the subject is asked to answer a query. The query includes a set of questions regarding the current situation. Answers are compared to the real state of the system and an overall SA score is calculated. Advantages of the method are its direct nature and avoidance of shortcomings of post-trial methods. However, the method has been criticized for intrusion into task performance, and difficulties with applying the method for real life activities (Endsley et al. 2003; Salmon et al. 2009). The method is primarily used in simulated environments, which give full control over the task (Bashiri and Mann 2015; Stanton 2005).

Real-time probe techniques are an alternative to freeze probe techniques and involve assessment of SA during task performance but with no freezing of the task (Salmon et al. 2009). The subject is asked to answer queries without stopping task performance. Indicators of the participant SA are response time and answer content. Endsley (2000) compared freeze and real-time techniques and reported that if the task cannot be simulated or frozen, real-time techniques may provide valid information.

Self-rating techniques are used for gaining a subjective assessment of participant SA

(Salmon et al. 2006). After each trial the participant is asked to rate experienced SA via a rating scale. Advantages of this technique are that it is easy, quick, low cost, and non-intrusive. Disadvantages are poor correlation with performance and poor recall.

Observer rating techniques require a subject matter expert to assess SA of the participant. The subject matter expert observes and provides a rating to participant SA during task performance (Salmon et al. 2006). Typically, the technique is used for 'in-the-field' assessment of SA. Advantages of observer rating technique are that it is non-intrusive nature and it applies to 'in-the-field' scenarios. Disadvantages include the subjective nature of the rating.

Performance measures involve relevant aspects of task performance to assess participant SA. Usually, it is very difficult to completely estimate SA by measuring task performance and this approach is used as a secondary SA assessment technique (Endsley et al. 2003). The problem with using performance measures for SA assessment is that a participant may have good situation awareness but perform the task poorly because of incorrect decision making (Scholtz et al. 2004; Vidulich et al. 1994).

Typically, estimation of SA involves a combination of several techniques (Endsley et al. 2003). A study that assesses SA of an autonomous machine supervisor might involve real-time probe and self-rating as primary techniques and performance measures as a secondary assessment technique. Other techniques do not fit well with that type of study. The freeze probe technique has been criticized for its intrusive nature and the observer technique is too subjective (Salmon et al. 2006).

2.4 Simulators in human factors studies

Simulators are widely adopted for training, design, and research purpose. (Lehto and

Landry 2012; Sandom and Harvey 2009). Studies in a simulated environment have advantages over studies in the real world. Usage of simulators ensures high flexibility, control over study variables, low cost, and safety of the experiment (Fitts 1951). Simulators are used for assessment of different parameters in human factors research. A driving simulator was used to estimate driver SA in critical driving situations (Plavšić et al. 2010), SA of an autonomous vehicle supervisor (Scholtz et al. 2004), and mental workload associated with the driving task (Pauzié 2008; Young and Stanton 2004). In the agricultural domain, simulators have been used to assess various aspects of human-machine interaction. For example, a tractor driving simulator was used to study the effect of lightbar characteristics on mental workload of a tractor driver (Dey and Mann 2009; Ima and Mann 2003), influence of automation on mental workload of tractor air-seeder system operator (Bashiri and Mann 2013), effect of cues on driving a tractor (Karimi and Mann 2008), and effectiveness of implement monitoring systems (Rakhra and Mann 2013). Assessment of user interface designs also involves simulation (Galitz 2007).

2.5 Objectives

In the literature review, problems associated with autonomous machine supervision and methods for their investigation were discussed. While most researches are focused on the improvement of autonomous machines, very little effort has been spent on the development of control interfaces (Yanco et al. 2004). Very few studies were conducted in the domain of user interfaces for autonomous machine supervision.

The main objective of the research was to determine the importance of live-video for remote supervision of an autonomous agricultural machine and to provide recommendations for interface designers. The hypothesis of the research was that the presence of live-video would increase the supervisor's SA and help to improve understanding of machine status.

3 Materials and Methods

It was necessary to create an autonomous agricultural machine control interface simulator (AAMCI simulator) to conduct the experiment. The simulator needed to create a realistic model of the supervisory task. It was required to show video footage, provide information about the machine status via indicators synchronously with video, and stage malfunctions of the agricultural machine to simulate problems.

An agricultural sprayer was selected for the AAMCI simulator. The sprayer provides some advantages for the experiment over other types of agricultural machines. First, the work process is fairly simple and straight forward. All the operations occur above the soil surface and can be easily shown by cameras. Second, it is relatively easy to stage malfunctions of the sprayer. The operator has control over boom position above the ground, tractor speed, tractor deviation from the path, and can turn nozzles on and off. Any of these parameters can be adjusted at any time during the field operation to stage a malfunction of the sprayer.

Figure 2 shows the experimental setup. It included a computer with two monitors, the Pupil Pro eye tracking platform, and paper forms for data collection. The following sections describe the AAMCI simulator, the video recording procedure, the experimental procedure, and data analysis.

The study was conducted in the lab environment using an autonomous agricultural machine control interface (AAMCI) simulator. The simulator is a computer program that simulates one possible autonomous machine supervisor interface. The following sections describe the interface and program code of the simulator.

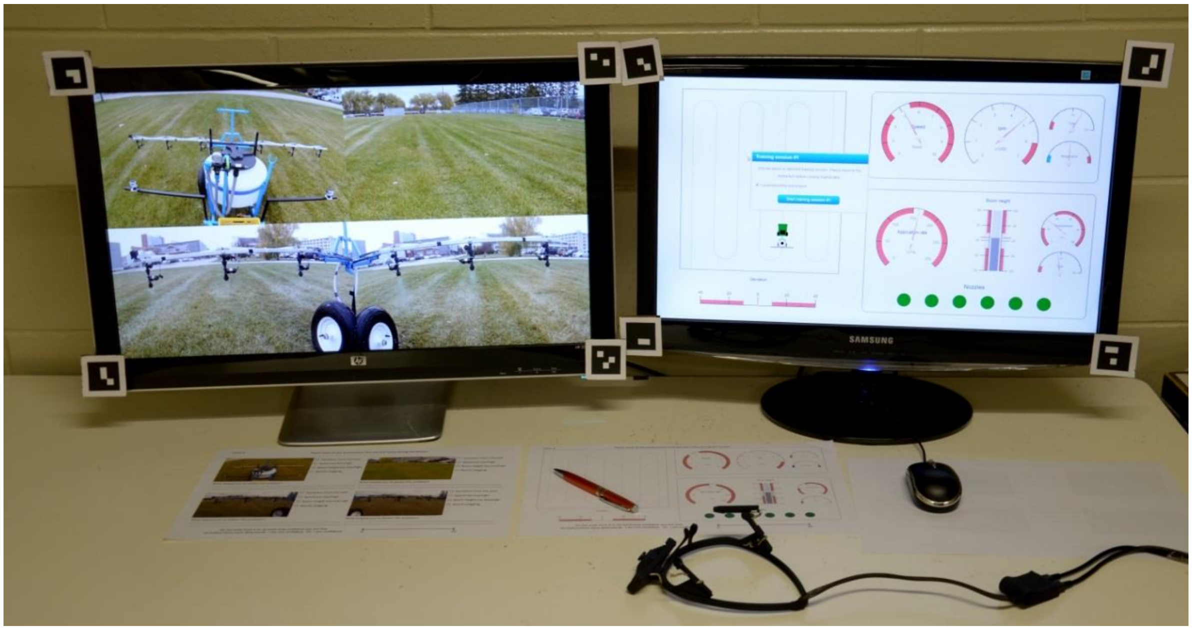

Figure 2. The experimental setup

3.1 The autonomous agricultural machine control interface (AAMCI) simulator

3.1.1 The simulator description

The simulator utilized two computer screens to provide information to the supervisor. The left screen (Figure 3) showed the video footage from four cameras mounted on a plot size sprayer. The prerecorded video footage was used to maintain consistency and repeatability of the experiment. Information about the video recording procedure is provided in section 3.1.3.

The camera positions were selected with the idea of providing as much detail about the sprayer and the spraying process as possible. Camera 1 was mounted on the tractor and provided a general view on the sprayer (Figure 3a). The image from the camera could help to understand status of the sprayer as well as to detect both deviation from the path and speed changes. Camera 2 was mounted on the right end of the boom and was faced forward. The image from camera 2

(Figure 3b) could help detect obstacles in front of the sprayer, path deviations and speed changes. Cameras 3 and 4 were mounted on the brackets at the same level as nozzles and in the center of the right and left booms, respectively. The purpose of these cameras was to provide a detailed view of the nozzles and help detect nozzle clogging. However, it was also possible to detect path deviation and speed changes using these cameras.

Figure 3. Left screen of the AAMCI simulator

a) general view camera; b) front view camera; c) right boom camera; d) left boom camera

The right screen (Figure 4) provided information about the agricultural machine status via icons and indicators. The indicators and icons were selected based on the indicators that are typically present on an agricultural tractor and sprayer. Shape and color of the indicators followed typical indicator design with standard functionality. The size of the indicator was chosen depending on the importance of the parameter for the spraying process. The small indicators (fuel and tank level, and engine temperature) have no direct relation to the spraying task and their values typically do not change quickly. The value of pump pressure itself is not important for the spraying task because application rate is a function of speed and pump pressure. The indicators were arranged based on the relation to the tractor or sprayer.

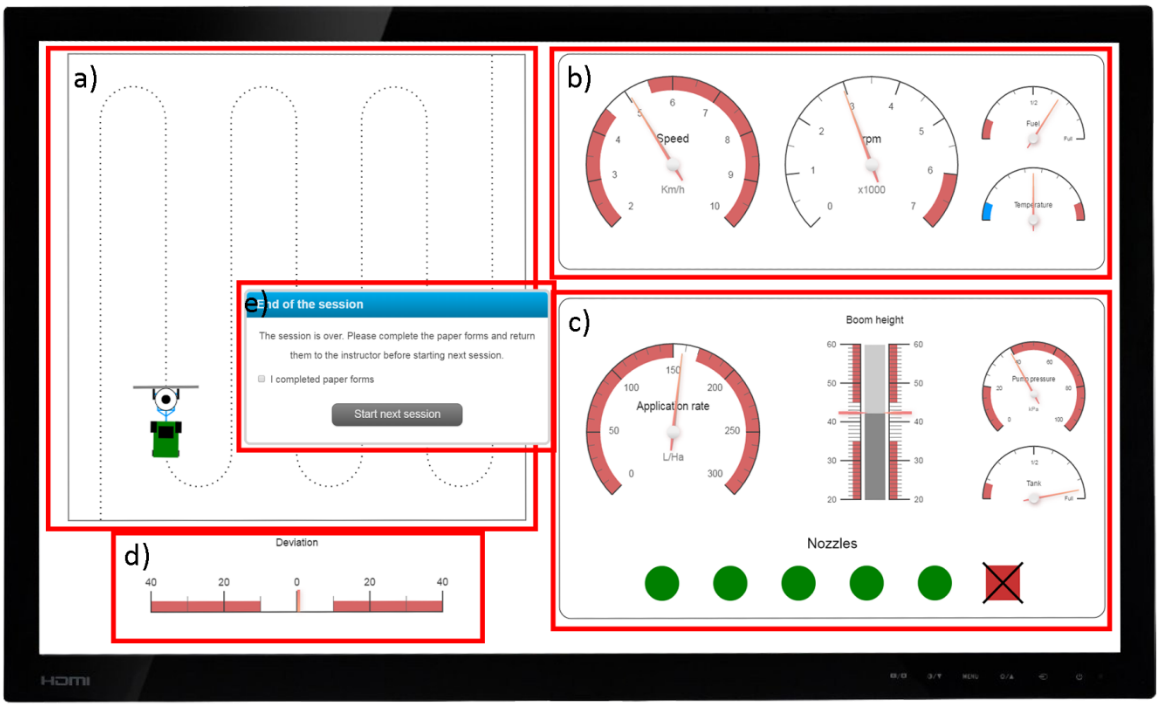

Figure 4. Right screen of the AAMCI simulator.

a) field scheme with tractor and sprayer icons; b) indicators related to the tractor; c) indicators related to the sprayer; d) deviation indicator; e) pop-up window

The field scheme with tractor and sprayer icons (Figure 4a) provided information about current position of the tractor on the field. Indicators related to the tractor were grouped in the top right corner (Figure 4b). The indicators included (left to right): speedometer, tachometer, fuel level indicator, and engine (coolant) temperature indicator. Indicators related to the sprayer were grouped in the bottom right corner (Figure 4c). The indicators included (left to right): application rate indicator, boom height indicator, pump pressure indicator, tank level indicator, and nozzle clogging icons in the bottom. The deviation indicator was located in the bottom left corner (Figure 4d). Information on both screens was synchronized manually.

A control interface (Figure 5) presented by New Holland (New Holland 2016) along with the prototype of the autonomous tractor has a lot of similarity with the interface that was developed for the study. One screen provides up to four live views from cameras mounted on the tractor, the second screen shows field and tractor's progress, and the third screen shows current state of the tractor and implement via indicators and enables their modifications. The designers leaned toward the same idea of multiple screens and similar layout of the information sources on the screens. Thus, the results of the study might be useful for future improvement of control interfaces.

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for copyright reasons.

Figure 5. The CNH Industrial autonomous tractor control interface (newholland.com).

3.1.2 Programming of the AAMCI simulator.

The AAMCI simulator was created using web technologies. The base of the simulator is an HTML web page. Content of the page was drawn and animated using JavaScript. JavaScript was selected as a programming language because it is a light, flexible, and relatively simple language. There are many free powerful libraries for JavaScript which can significantly simplify programming. It is possible to run the program on almost any device that has a web browser.

Libraries jQuery 3.0 (jQuery 2017) and Canvas Gauges (Canvas-gauges 2017) were used for the project. jQuery is a JavaScript library designed to simplify scripting of HTML. It is free and open-source software. Canvas Gauges is open-source software based on HTML-5 specification and uses the Canvas application programming interface (API) (Mozilla Developer Connection 2017). The library allows the use of JavaScript to create animated linear and radial gages on an HTML page. It has built-in tools for customization of the gauges which helps the programmer to set the gauges to fit a particular interface. The library was used for drawing all the indicators of the simulator.

Figure 3 and Figure 4 show what the participant saw at the beginning of the experiment. These images were used for explanation of what is on the screens, how the simulator works, and how to interact with the simulator. The participant's interaction with the simulator was limited to a pop-up window (Figure 4e). The pop-up window included the checkbox, "Start next trial" button, and short directions about what to do next. The button was inactive until the participant confirmed that paper forms were completed by clicking the checkbox. By clicking the start button, the participant ran two processes. The first one is the video playback and the second one is the animation of the indicators and field scheme. Programming of the first process was fairly simple because JavaScript has built-in functions to control video playback. The program took corresponding video file according to current trial number and started the playback. The participant had no control over video except starting the playback and could not pause or stop the video. The second process started counting the number of seconds from the trial start. Every second the program fed a new value to every indicator. The Canvas Gauges library calculates indicator animations by itself. It means that after the defined time (in this case it was one second) indicators showed the value that was fed. This process went continuously and created smooth animation of the indicators.

The animation of the tractor and sprayer movement along the path on the field scheme was more complex. There is no ready to use solution for this task. The animation was performed by using Canvas API function *window.requestAnimationFrame().* The function creates smooth animation by calling the next animation frame when the system is ready to paint the frame (Mozilla Developer Connection 2017). A typical personal computer can sustain a frame rate in the range of 30-50 frames per second. This frame rate is sufficient for smooth animation without noticing single frames. The animation of the tractor and sprayer movement is reduced to a calculation of their position at the new frame. The calculation is relatively simple during the straight movement and fairly tricky during turns. Realistic animation of the turns takes into account that tractor and sprayer are connected at the hitch point and follow different trajectories. Instant center of rotation lays on the virtual extension of the tractor rear axle and varies depending on the tractor base length, turn radius, wheel slippage, and so on (Dudnikov and Shchitov 2011). The animation was simplified in a way to achieve a believable movement without complex calculations. It was assumed that the sprayer and the tractor moved along the same trajectory and the turn radius was constant. Given the relatively small size of tractor and sprayer icons on the screen the animation was acceptable for this project.

Each trial included a predefined set of five or six sprayer problems. Two or three of them were presented on the video footage and the respective indicators were synchronized with the video. The remaining problems were shown only by indicators. Thus the simulator code included a table with indicator value for each trial and time stamp when an indicator value should be changed. Each trial had an average length of two minutes and stopped at a random point with the screen going blank.

3.1.3 Video recording setup and procedure.

The video was recorded using a plot size tractor and a lawn sprayer. A Bolens tractor Model 2028 with removed lawn cutting deck was used as the tractor. Setter's trailer sprayer Model # SE-TR12-H25G12B was modified to enable the staging of malfunctions. A general view of the setup for the video recording is presented in Figure 6. The modifications of the sprayer are indicated with Roman numerals. Standard nozzles were replaced with nozzles with solenoid valves (Figure 6a, III). The nozzle control box (Figure 6a, I) was placed in an accessible area near the operator seat. Each of the nozzles had an individual switch and it was possible to turn on and off the nozzles at any moment, thus staging problems with nozzle clogging. A lifting system (Figure 6b, II) was installed that allowed the operator to control the boom position and stage another problem with the sprayer – the wrong boom height. The operator also had control over tractor speed and deviation from the path. As a result, the setup allowed the staging of four sprayer problems during the spraying – nozzle clogging, incorrect boom position, incorrect tractor speed, and tractor path deviation.

a)

b)

Figure 6. Plot size tractor and the sprayer modified for video recording

I – Nozzle control box, II – Boom lifting system, III – Nozzles with solenoid valve. 1 – General view camera, 2 – Forward view camera, 3,4 – Nozzle view cameras.

Four GoPro cameras were mounted on the sprayer and tractor. Positions of the cameras are presented in Figure 6 and indicated with numbers 1-4. A general view camera (Figure 6, position 1) was mounted on the tractor facing backward. The camera recorded a general view of the sprayer and was intended to provide information about the general status of the sprayer to the supervisor. It was not supposed to show specific details but help the supervisor to estimate the situation with a quick glance. A forward view camera (Figure 6, position 2) was located on the end of the right boom facing forward. The purpose of the camera was to help the supervisor to detect deviation of the sprayer and it could also help to estimate the speed of the tractor. Nozzle cameras (Figure 6, positions 3 and 4) were placed on the mounts. Mounts were designed so the cameras would be located in the center of the right and left boom, respectively, and approximately on the same height as the nozzle spraying cones. Each of the cameras recorded three nozzles and was intended to help to detect nozzle clogging.

The video was recorded on the University of Manitoba Fort Garry campus on a rectangular lawn area near Service 7 Street South. It was necessary to record a video clip with staged malfunctions for each of the twelve experimental and three training trials. A recording plot was designed in a way to ensure lack of patterns and equal distribution of the sprayer problems over the video clips. The sprayer problems were staged manually during the recording according to the plot. For each trial, the videos from four cameras were synchronized and merged into one clip using video editing software (Flash-Integro LLC 2017).

3.2 Experimental phase

3.2.1 Participant procedure

Seventeen participants volunteered for the study. Participants were between 19 and 40 years old (mean 27.5); 14 of them were male and 3 were female. Five participants had experience with farming and two of them had experience operating an agricultural sprayer. The study was approved by The University of Manitoba's Education and Nursing Research Ethics Board (Appendix A) and all participants signed the informed consent form (Appendix B) before beginning of the experiment.

The experimental procedure included verbal explanation of the study goals and the role of the participant, four training trials, and two experimental sessions with a ten minute break between them. Each experimental session included twelve trials (six pairs) with an average length of two minutes. The trials within one pair provided the same information about the sprayer status using one of two ways: 1) graphical indicators supplemented by live video (referred as Case 1 in the following sections) and 2) solely with the use of graphical indicators (referred as Case 2 in the following sections). The order of the trials within the experimental sessions was randomized for each participant to minimize the influence of learning on the results.

Each participant performed twelve Case 1 and twelve Case 2 trials. During Case 1 trials, the problems of the sprayer were presented in three different ways. Case 1a problems were the problems that could be shown only via indicator (i.e. engine RPM, engine temperature, fuel level, application rate, pump pressure, and tank level). None of these problems could be shown using video footage. Case 1b problems were the problems that were shown by indicator and video footage synchronously (i.e. tractor speed, boom height, deviation, and nozzle clogging). The participants could use either screen to detect the problem. Case 1c problems were the problems that were shown only via video footage. This situation simulated sensor failure. That case included the same problems as the Case 1b. Participants were informed about all possible ways that problems could be shown during the explanation at the beginning of the experimental procedure.

The participants were provided with two paper forms (Figure 7). Form A was used for indication of the problems detected with the help of the live video. Form B was used for indication of the problems detected with the help of the indicators.

Participants were instructed to immediately mark any sprayer malfunction detected during the trial on the appropriate paper form. It was possible to detect four malfunctions using video: nozzle clogging, incorrect forward speed, sprayer deviation from the path, and incorrect boom height. Form A included four corresponding checkboxes and a place for comments near each image. The participant could quickly indicate which problem was detected and which camera helped to do it.

In addition to the four mentioned malfunctions, indicators could also show problems with engine rpm, fuel level, engine temperature, application rate, pump pressure, and tank level. Each indicator had a white zone and one or two red zones. As long as the needle stayed inside the white zone it was considered as normal operation. If the needle entered any red zone it was considered as a tractor or sprayer problem and the participants were told to mark the approximate position of the needle on the corresponding indicator and thus indicate that the problem was detected. In the case of the nozzle clogging, the participant was told to draw any mark over the corresponding nozzle icon.

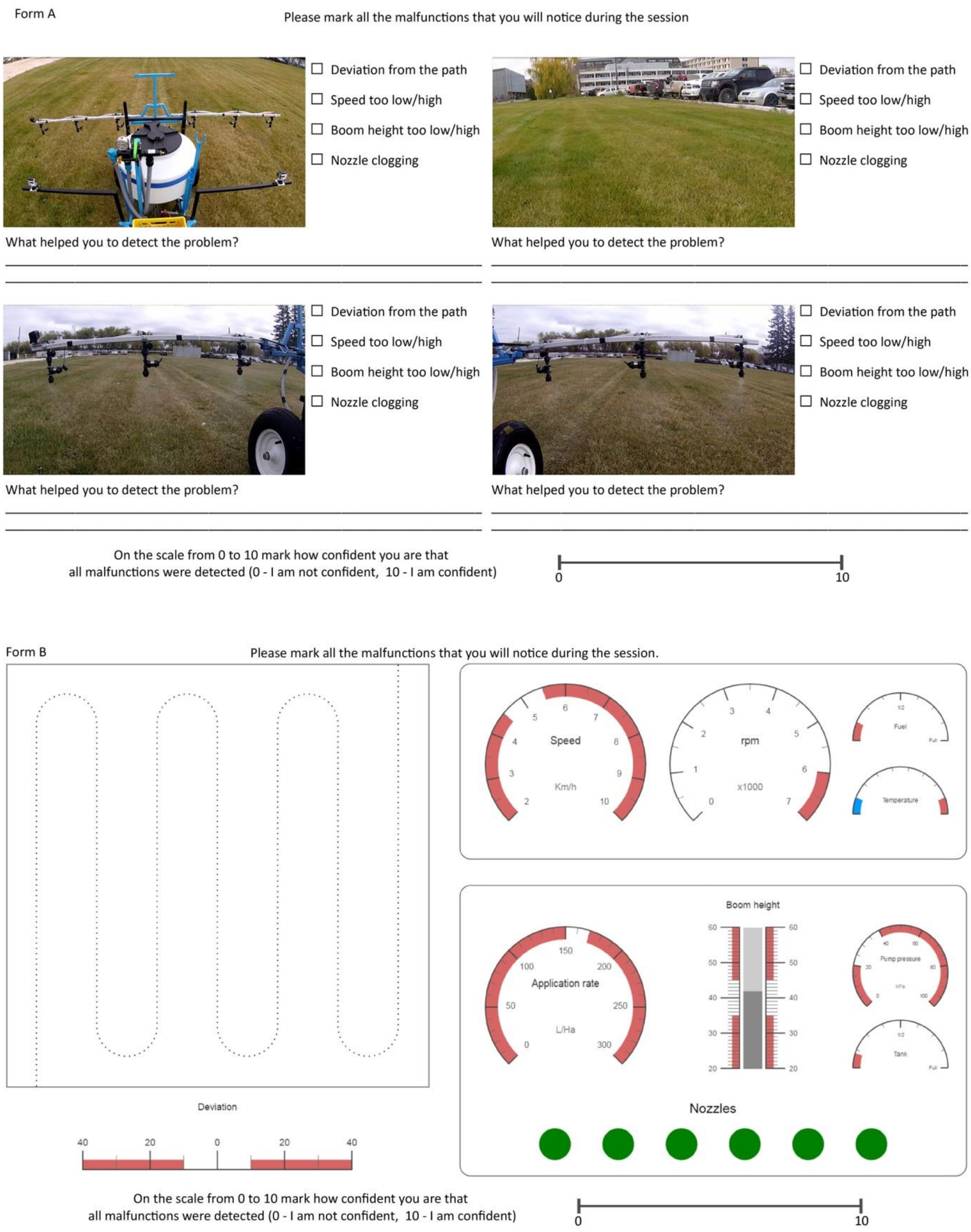

Figure 7. The paper forms used by participants to indicate problems that were detected

A scale from 0 to 10 for self-assessment of confidence level was placed at the bottom of both forms. Zero on the scale meant no confidence about machine status and 10 meant absolute confidence. At the end of each trial, participants were asked to estimate their level of confidence that all the problems had been detected by drawing a line on the scale. The participants were asked to provide separate evaluation for left (video) and right (indicators) screens.

At the end of the experiment, participants were asked to answer a questionnaire (Appendix C). They could express their opinion about the usefulness of the video footage for the supervisor of an autonomous agricultural machine and provide comments.

3.2.2 The Pupil Pro eye-tracking platform

The Pupil Pro eye tracker (Figure 8) was used during the study along with the simulator and the paper forms to collect data. The Pupil Pro has shape similar to regular glasses but has no lenses (Pupil Labs 2017). One camera mounted beside and below an eye captures pupil position. A world (frontal) camera records general direction of gaze. The Pupil Pro software uses special markers to define surfaces (Figure 2). Left and right screens of the simulator were defined as the surfaces of interest. The software calculates gaze direction by combining data from the two cameras.

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for copyright reasons.

Figure 8. The Pupil Pro eye tracker (Pupil Labs 2017)

3.3 Data analysis

The study included assessment of participant performance, eye glance behavior, and subjective responses. Description of methods that were used for the assessment is provided in the following sections.

3.3.1 Participant performance

The participant performance was estimated by calculating the ratio of correct answers to total number of answers. The answer was considered to be correct if the simulator showed a problem by indicator, video or both and the participant indicated it on the corresponding paper form. In case the problem was presented but the participant did not indicate it or if the participant indicated that he/she noticed a problem but actually it did not happen it was considered as an error.

The participant performance was compared for Case 1 and Case 2 trials. Also it was used to compare different ways to present problems: indicator only (Case 1a), video and indicator (Case 1b), and video only (Case 1c). The performance of participants with and without farming experience was compared to each other. Influence of fatigue on the performance was estimated by comparing the performance results during the first and second experimental sessions.

3.3.2 Subjective responses

The participant responses for confidence level were analyzed in the same fashion as the participant performance. The scores for Case 1 and Case 2 trials were compared. For Case 1 trials, the scores for left and right screens were compared as well.

Questionnaire answers were analyzed to understand subjective opinion of the participants about importance of the live video footage. Also, participant comments and observations by the primary investigator have been included in the analysis.

3.3.3 The Pupil Pro system outcome

The Pupil Pro platform provides advanced tools for data analysis. One of them, Surface Tracker plug-in, was used for analysis of the gaze distribution. Special markers were placed on the surface of interest to make the plug-in work. The markers were placed on both of the screens. During the analysis, these markers were used to define surfaces and the plug-in calculated number of gazes for left and right screens. The plug-in can generate gaze distribution heatmaps similar to what is shown in Figure 15. The heatmaps provided visual information about the areas on the screens that received more attention from the participant. Thus, number of gazes for left and right screens and gaze distribution heatmaps were obtained for most of the trials. Unfortunately, for some of the trials, gaze distribution data were corrupted due to software failure. For those trials, a manual method was applied to assess gaze distribution.

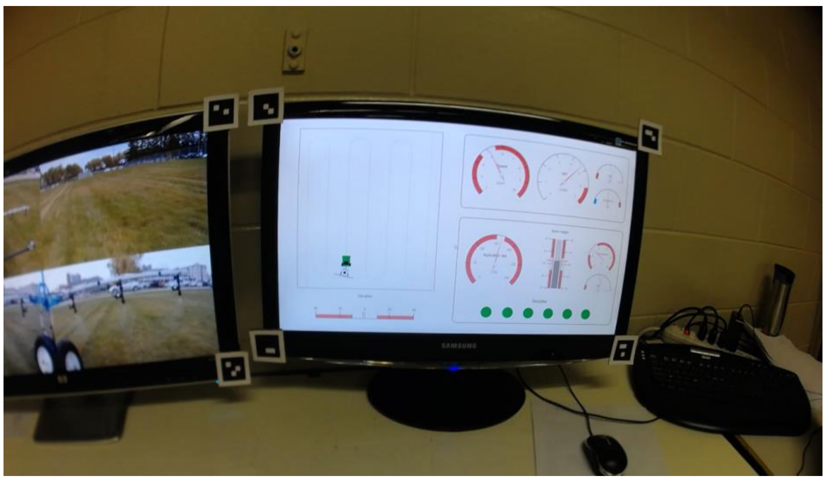
3.3.4 Manual method for assessment of gaze distribution

Computer systems for assessment of gaze distribution are not perfect. It might happen that data are partially or completely corrupted due to hardware or software failure. During the study the data from the Pupil Pro system were corrupted for some of the trials due to software errors. The records from the world camera were still available but data about gaze directions were corrupt. Instead of simply removing the sessions from the analysis it was decided to try to estimate gaze distribution between left and right screens manually.

VLC Media player for Ubuntu (VideoLAN 2017) was used to analyze the videos. Time plug-in (Time 2017) for the player was used to show milliseconds during the video playback. Figure 9 shows typical pictures that were received from the world camera. Images shown on Figure 9a and Figure 9b were considered as the situation when the participant was looking on the left screen and right screen, respectively. Figure 9c shows the image that was considered as a threshold for transition between left and right screens.

The videos were played at half of the normal speed. The frame of the video when the participant clicked the start button was considered to be the starting time. The frame of the video when the screens went blank was considered as the ending time. The starting and ending times for each period of time when the participant was looking on the left or right screen were recorded. Periods of time when the participant was putting marks on a paper form were excluded.

a) 

b) 

c) 

Figure 9. Direction of the participant gaze.

Left screen (a), right screen (b), threshold for transition between left and right screens (c).

Comparison of the gaze distribution results for manual method and software output was conducted to validate the method. Table 1 shows ten trials for which the software output was compared with the manual method. Average difference between software output and manual assessment was observed to be 1.7%. The difference was considered acceptable and the manual method was used to assess trials where software output was corrupted. Appendix G contains gaze distribution data for all trials. Trials where manual method was used are highlighted with italics.

Table 1. Percentage of time the participant was looking on the left screen*.

Trial #**	Software output	Manual assessment	Absolute difference
P4 T9	26.0	30.5	4.5
P5 T11	47.1	50.7	3.6
P6 T3	45.3	47.8	2.5
P7 T8	55.1	50.3	4.8
P8 T11	33.2	34.0	0.8
P10 T1	54.0	53.4	0.6
P11 T5	30.0	28.6	1.4
P12 T4	43.0	43.9	0.9
P15 T15	37.1	37.9	0.8
P17 T1	84.6	84.7	0.1
		Average difference	1.7

* Percentage for right screen can be calculated using formula 100-(left screen percentage).

** Trial number designation P4 T9 stands for Participant 4 Trial #9 and so on. List of trials order is available in Appendix E.

4 Results and Discussion

Results of the study are presented in the following sections. Four types of data were collected to estimate the importance of real-time video footage for a remotely located supervisor. Paper forms were used for estimation of participant performance and for participant self-assessment of confidence in the sprayer status. The Pupil Pro eye tracker was used to collect information about gaze distribution for most of the trials. For some trials, gaze distribution was measured manually due to software failure. Subjective opinions were collected at the end of the experimental session. Additionally, observations noted during the experimental sessions are presented and included in the discussion.

4.1 Participant performance

It was hypothesized that presence of live video footage would help the participants to detect the problems and that performance during Case 1 trials would be better than that during Case 2 trials. Figure 10 shows comparison of the participant performance for Case 1 (with video footage) and Case 2 trials (without video footage). Individual results for each participant can be found in Appendix F. The participants showed better performance during Case 2 trials. The difference between two cases of trials is 9.1% and is statistically significant (α=0.05). Unlike the expected results, the participants' performance was lower during the Case 1 trials. The percentage of the correct answers increased by 13% from 71.9% to 84.9% during Case 2 trials. In case of big size indicators (i.e. speed, engine rpm, application rate, and boom height indicators) the difference was 6.5%. It increased from 91.3% to 97.8%. The percentage of correct answers for the deviation indicator increased 9.4% from 83.5% to 92.9%. Most likely it happened because the live video footage was not as effective as indicators for problem detection. At the same time presence of the video footage forced the participants to share attention between two screens. The highest influence of the video footage presence was observed for problems presented by the small size indicators (i.e. engine temperature, fuel level, pump pressure, and tank level indicators). Nozzle clogging was the only indicator for which the participants showed almost the same performance (the difference was less than 1%).

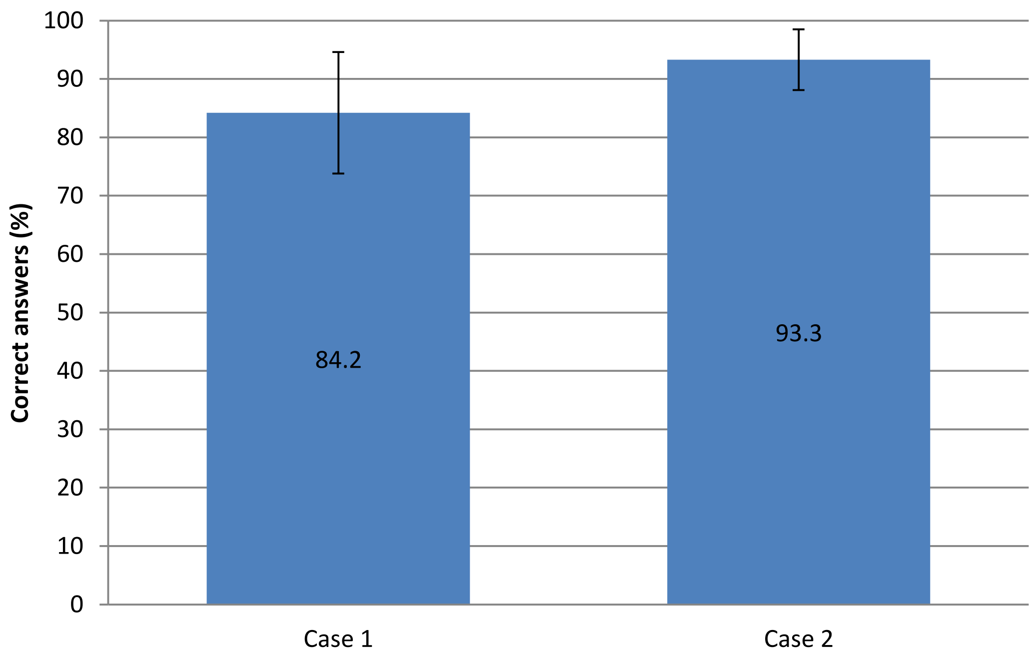


Figure 10. Percentage of correct answers for Case 1 and Case 2 trials.

Bars indicate 1s.d.

Figure 11 shows the participants performance for the different ways the problems were presented during Case 1 trials. The performance was almost identical for Case 1a and Case 1b problems when the participants used the indicators. However, the presence of the video footage increased the performance by 10.4%. The performance was relatively poor for the Case 1c problems (the problem was presented by the video footage only). The analysis of Case 1c problems showed that the video footage is relatively well suited for detecting some problems and is not suitable at all for detecting other problems. The nozzle clogging was detected in 35.3% cases and the wrong speed in 27% cases but the wrong boom height and the deviation was detected in only 2.7% and 0% cases, respectively. In any case, the results are significantly lower than for Case 1a and Case 1b problems. About 0.2% of the answers were false positive and all of them related to the camera images. Thus the results show that the video footage is not an effective way to detect sprayer problems. Additionally, many participants mentioned that even though it is possible to detect a problem using the camera it requires much more effort in comparison to indicators.

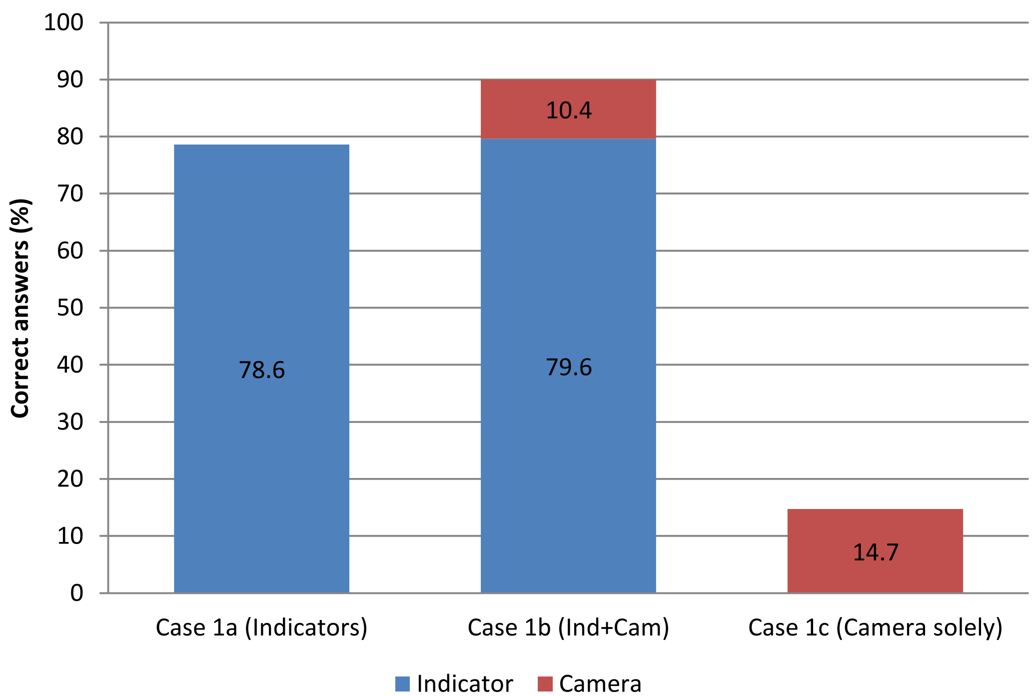


Figure 11. Percentage of correct answers for the different ways problems were presented during Case 1 trials.

4.2 Influence of fatigue on the participants performance

The influence of fatigue on the participants' performance was conducted by comparing the performance shown during the first and second experimental sessions (before and after a break). It was hypothesized that the performance during the second session would be poorer as the participants get tired, lose concentration, and miss more of the sprayer problems. Figure 12 shows results of the comparison.

The graphs show that the participants' performance was better during the second experimental session in all cases, although the differences were not statistically significant. The result might be caused by the effect of learning. Even though the participants had four training sessions it might be inadequate to enable full performance from the very beginning. Additional study is required to investigate this problem

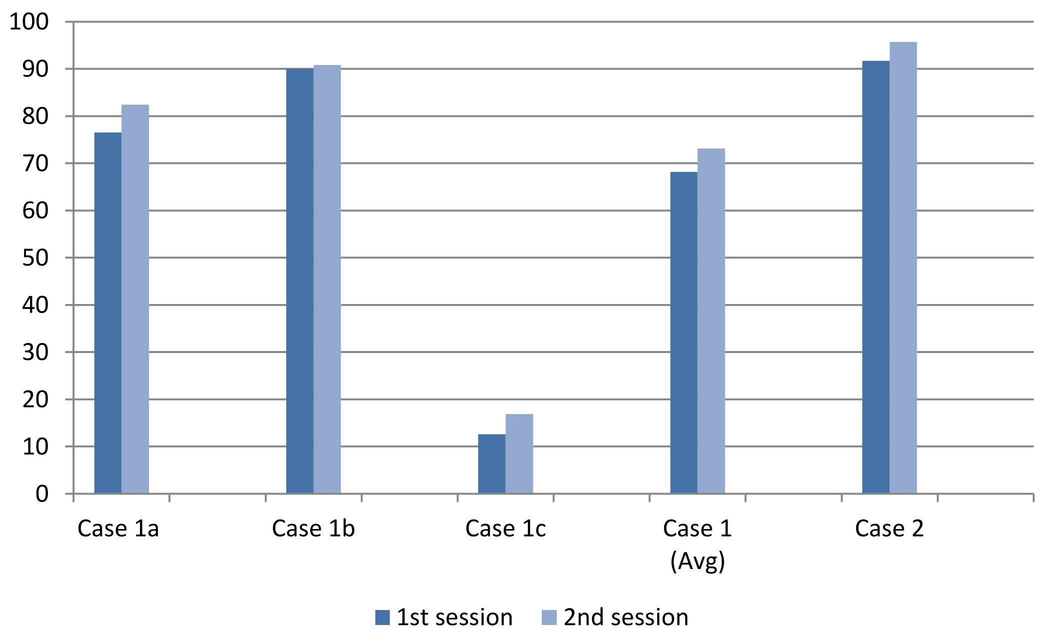


Figure 12. Influence of fatigue on the participant performance.

4.3 Performance of the experienced and inexperienced participants

The study involved seventeen participants. Five of them had farming experience. It was hypothesized that the farming experience would help them to perform the supervisory task better due to better understanding of the spraying process and the way the sprayer works. Results of the comparison are shown in the Figure 13.

The graph shows that the performance of inexperienced participants was better in all cases, but the differences are not statistically significant. The problem requires additional investigation with more participants. It might be found that the supervisory task is simple enough and does not require farming experience to ensure good performance.

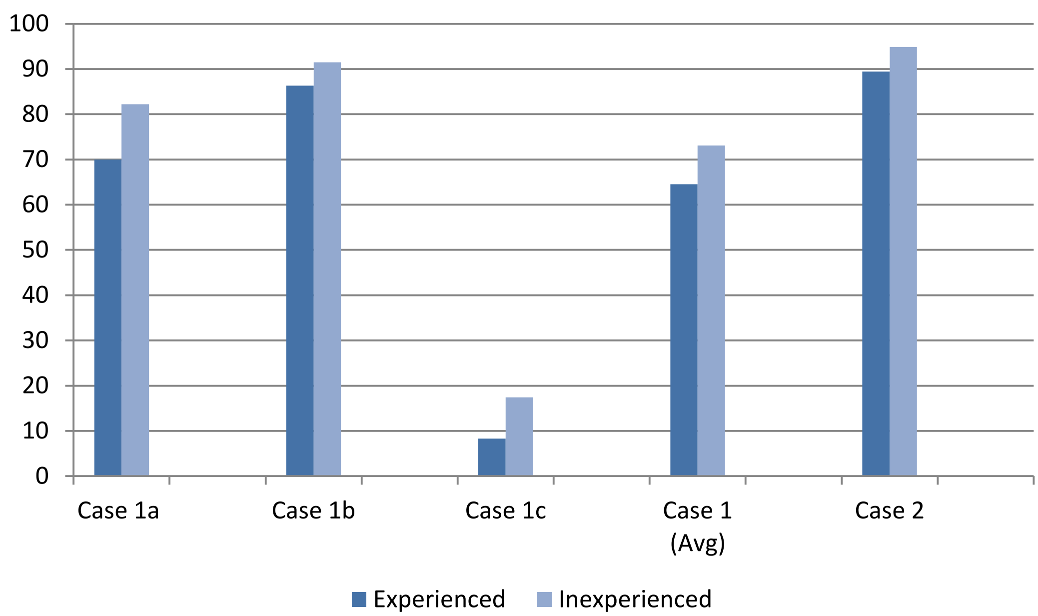


Figure 13. Comparison of the performance of experienced and inexperienced participants

4.4 Gaze distribution

The gaze direction data were received using the Pupil Pro software. Gaze distribution between left and right screens of the simulator was calculated for each trial. Figure 14 shows the gaze distribution during the course of the experiment. The graph includes all the Case 1 trials including training trials. The training trials are included in the analysis to emphasize changes in the participant's behavior.

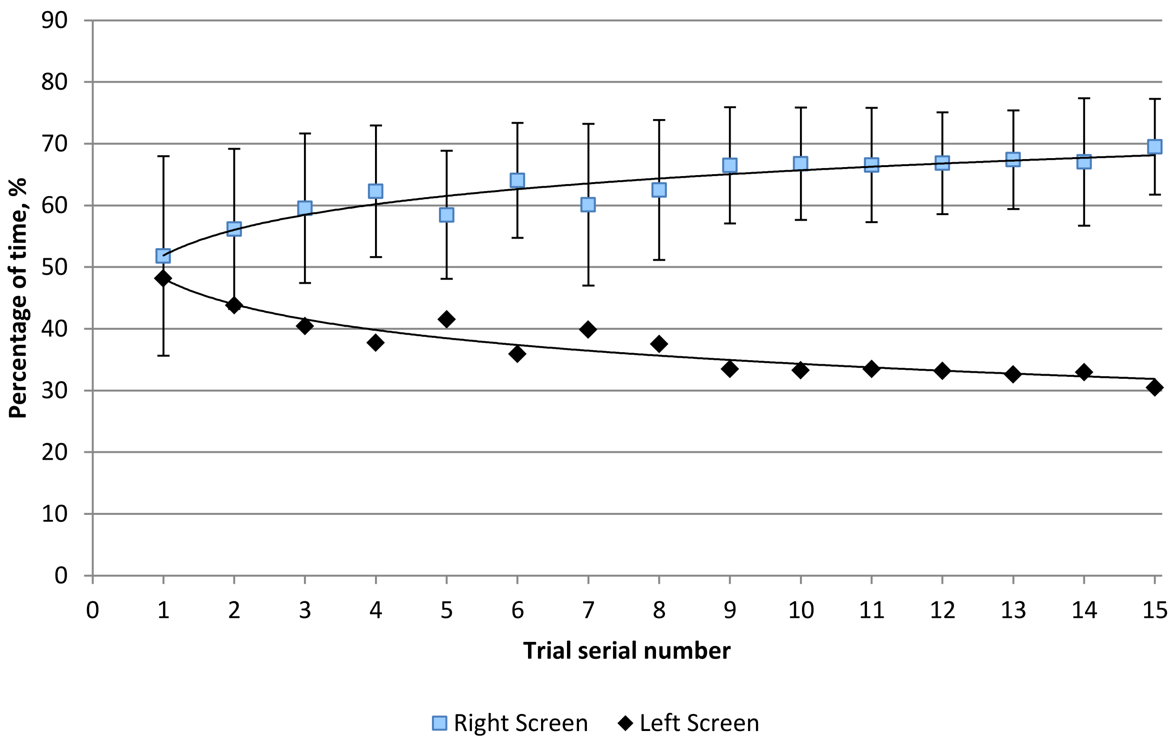


Figure 14. Dynamic of the gaze distribution between left and right screens

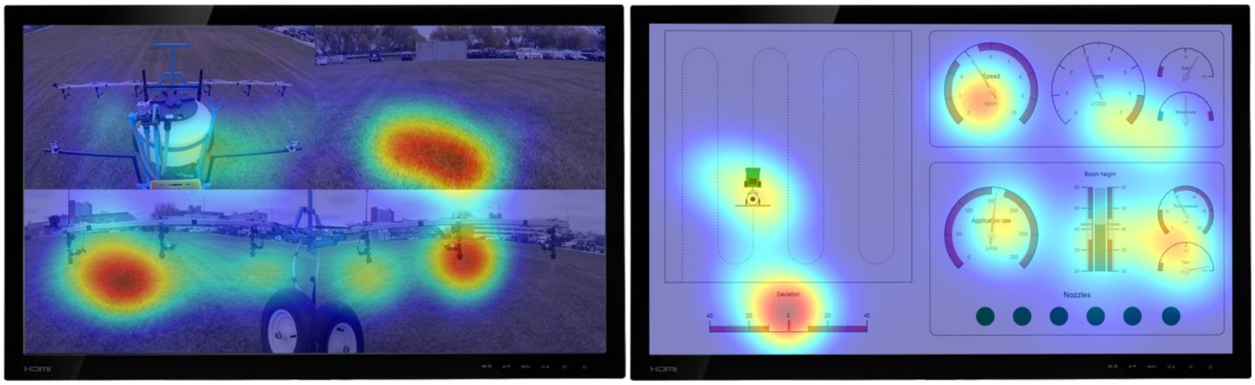
Bars indicate 1s.d.

The analysis showed that at the beginning of the experiment the participant's attention was distributed almost 50/50 between the screens. At the end of the experiment participants spent almost 70% of their time watching the right screen. Figure 15 shows typical gaze distribution heat maps. It includes a heat map for the first training trial, first and last experimental trials. The heat maps (Figure 15) provided the same results in visual format. It is clear that gaze distribution shifted from almost equal spread over the screens to the spots of high gaze concentration. On the left screen, almost equal attention to all four images changed to high concentration of the gazes on the nozzle cameras and much less attention to the other two images. The participants were focused on the nozzles trying to detect the nozzle clogging. The general and forward view cameras did not require constant attention because it was possible to estimate the situation with quick gaze.

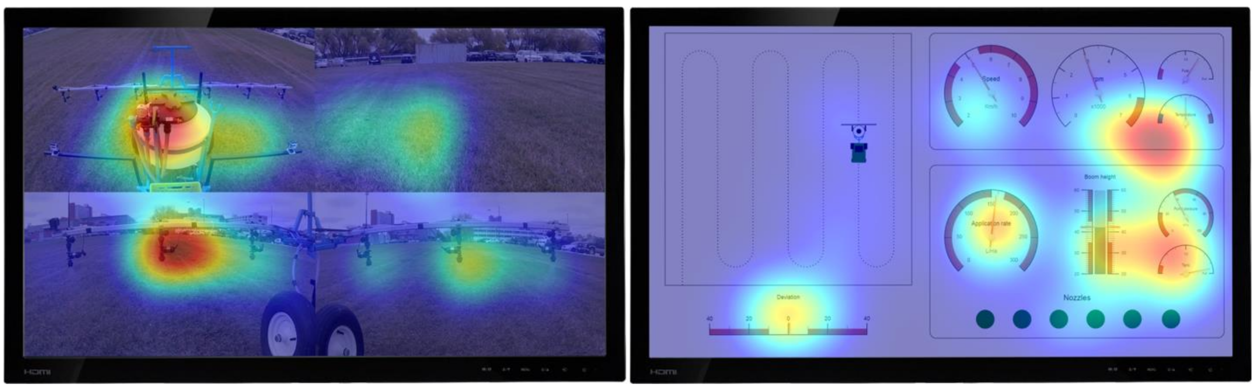
The participant attention was equally distributed over the right screen at the beginning and focused on the indicators at the end. The nozzle icons area (the bottom right corner) did not require the participant to focus on it and at the same time the nozzle clogging malfunction had very high rate of correct detection. It was 96.1% for Case 1 trials and 97.1% for Case 2 trials. It can be explained by the design of the nozzle icons. In case of malfunction the icon changed its color and shape from a green circle to a red square and Level 2 of Situation awareness was achieved. The rest of indicators ensured only Level 1 situation awareness and required more attention to achieve the same level of performance.

Dispersion of the gaze distribution ratio in the end of the experiment was 1.5-2 times lower than in the beginning. Thus, the behavior of the participants had a tendency to follow similar pattern. Based on the principal investigator observations during the experimental sessions the following pattern was found. At the beginning of the experiment the participants took quick, about 2-3 s, gazes to the left and right screens and constantly switched from one object to another. During the course of the experiment the participants' behavior became more calm and orderly. The gaze duration to the right screen extended to 5-7 s with focus on the indicators. The gaze duration on the left screen lowered to 1-2 s with focus on the nozzle cameras.

It was hypothesized that there is a correlation between the ratio of the left and right screens gaze distribution and the participants performance. However, the correlation analysis showed no correlation between the variables (correlation coefficient 0.19).



a)



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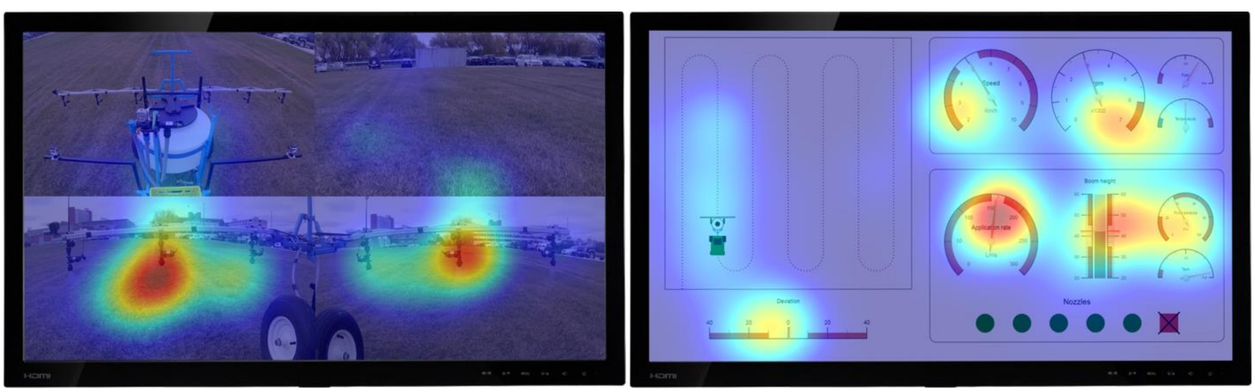

c)

Figure 15. The gaze distribution heat maps.

a) First training trial; b) First experimental trial; c) Last experimental trial

4.5 Subjective responses

Two types of subjective responses were collected. The first type was the subjective level of confidence in agricultural machine status and the second type was the answers for the questionnaire.

After each trial the participants estimated their level of confidence in the agricultural machine status by drawing a line on the 0 to 10 scale. The estimation was received for the left and right screens separately. The participants' responses were converted to 0-100% format. Figure 16 shows the level of confidence for Case 1 trials. The average for the left screen (camera images) was 56.0% and for the right screen (indicators) was 81.3%. The difference is 25.3% and statistically significant.

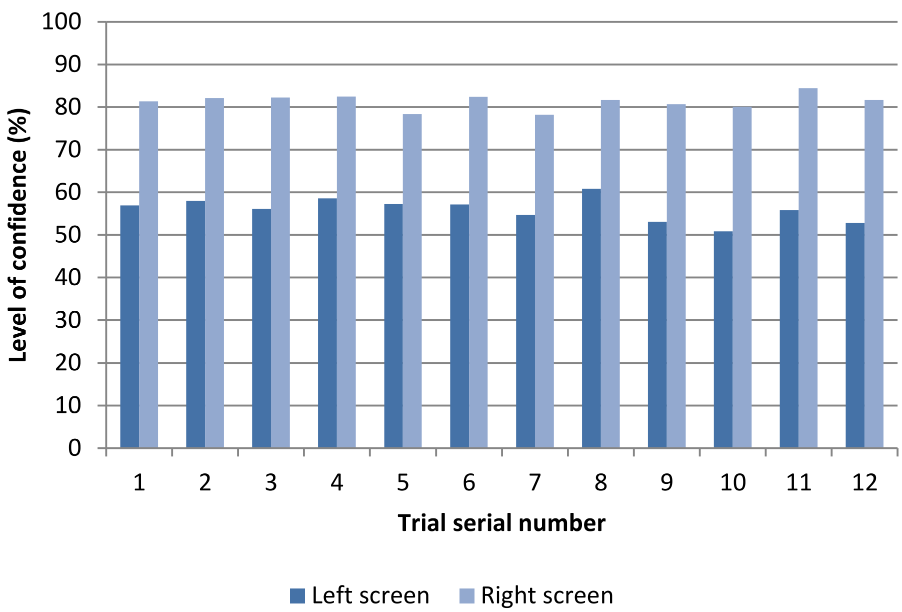

Figure 16. Level of confidence in the agricultural machine status for Case 1 trials.

Figure 17 shows comparison of the confidence levels for the right screen (indicators) for Case 1 and Case 2 trials. The average level was 81.3% for the Case 1 trials and 87.4% for Case 2 trials. The difference is 6.1% and is statistically significant. The information on the right screen was the same for Case 1 and Case 2 trials. Thus, the presence of the video footage decreased the level of confidence by 6.1%.

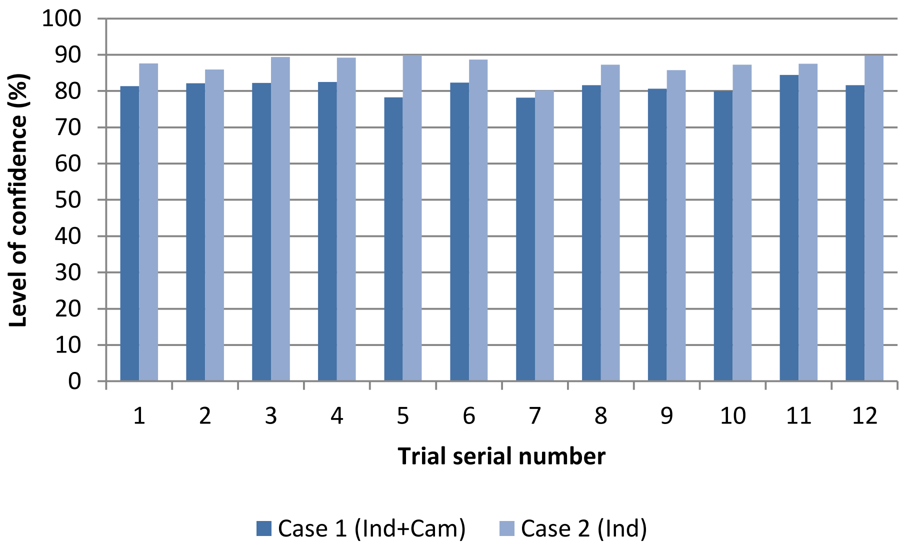

Figure 17. Level of confidence in the agricultural machine status for Case 1 and Case 2 trials.

At the end of the experiment the participant answered the questionnaire (Appendix C) and could write comments about the experiment. The comments are provided in Appendix D. The analysis of the responses provided below.

All the participants indicated that the video footage should be supplied to the supervisor of the autonomous agricultural machine. However only 17.6% preferred to see the video all the time and 82.4% preferred to see it on demand. At the same time 76.4% of the participants indicated that the presence of the video footage increased their level of understanding of machine functions, 11.8% noted the decrease, and 11.8% found no effect. More than a half of the participants (52.9%) indicated that they felt more confident when the video footage was provided, 11.8% felt no difference, and 35.3% indicated that they felt less confident.

About 82.4% of the participants found the video footage helpful in detection of the agricultural sprayer malfunctions. In particular, the video was indicated as a helpful tool for detection of nozzle clogging by 76.5% of the participants, speed changes (35.3%), wrong boom height (11.8%), and path deviation (5.9%).

4.6 Discussion

The results obtained in the study showed that a supervisor of autonomous agricultural machines relies on video footage significantly less than a supervisor of rescue robots. In the case of remote supervision of rescue robots, an operator spends most of the time watching live video (Baker et al. 2004) while a supervisor of autonomous agricultural machines spends about 70% of the time watching indicators and only 30% watching video. Figure 14 clearly shows that the live video is a secondary source of information about machine status for a supervisor. The amount of time the participants spent watching video gradually decreases as the participants get more familiar with the task.

Most likely the difference will be even greater with more emphasis on interface design. The interface was designed in a way to replicate indicators that are used in agricultural sprayers and provide the same information that is available for the sprayer operator. However, the computer interface is more flexible tool than analog indicators and can provide the same information in more convenient to perceive format. It is possible to program indicators to grab the supervisor’s attention when it is necessary by changing color, blinking, making alarm sounds, and so on. Under some circumstances the software can give hints to the supervisor about what to do to solve the problem. Thus, second and third levels of the situation awareness might be achieved. Even though the study results showed that the current interface design works well from the point of view of delivering information about the sprayer status to the supervisor it might happen that a different design will be more effective.

Camera images are not suitable for problem detection. It is better to use them to show a general view on the tractor environment while important information about machine status can be provided via indicators linked to sensors. This conclusion is similar to the recommendations provided by other researchers (Johnson et al. 2009; Moorehead et al. 2009).

4.7 Limitations

The small number of participants with experience in operating an agricultural sprayer might be considered as a limiting factor. Even though the comparison of the performance of experienced and inexperienced participants was conducted, it is not possible to make meaningful conclusions. Future studies of this type should include a larger number of experienced participants.

A factor of the experiment that may be considered limiting is that the Pupil Pro eye-tracker system did not work well all the time. Even though it allowed to collect gaze direction information for most of the trials it was necessary to manually estimate gaze distribution for some of the trials due to software failure. Additionally, the eye-tracker requires very fine calibration and gentle handling. This features limited gaze distribution analysis to the left and right screens as a whole without dividing them into zones. Usage of a more sophisticated eye-tracking system could potentially provide interesting information about gaze distribution within screens.

Finally, it was observed that many of the participants seemed confused with assessment of their level of confidence in agricultural machine status, and would often rate how difficult they found to detect the sprayer malfunctions (basically mental workload) instead of their confidence. Future studies should consider separate assessment of mental workload associated with the supervisory task, and subjective level of confidence.

4.8 Conclusions and recommendations

The study was focused on assessing the importance of live video footage for the remotely located supervisor. It was found that live video is not an effective tool for the detection of agricultural sprayer malfunctions. The participants' performance, estimated by the number of correctly detected malfunctions, was lower when the video footage was provided.

The analysis of subjective opinions showed that the participants felt more secure when the video was presented. Despite the fact that most of the participants indicated that it was hard to detect the malfunctions using video they would prefer to have live video on the screen either all the time or on demand. Additionally, more than ¾ of the participants indicated that the video footage helped to better understand machine functions.

Analysis of the gaze distribution revealed that the participants' attention shifted to the right (indicators) screen. At the beginning of the experiment the ratio between left and right screens was about 50/50, and at the end of the experiment it was about 30/70.

Based on the experiment results and observations, the following recommendations should be considered by the autonomous machine interface designers:

- the supervisor of an autonomous machine(s) should have an ability to get live video from the machine when it is needed. It is not necessary to provide the video all the time but it is important to include it as an option.

- it is not effective to use video cameras for an agricultural sprayer problem detection. It is better to delegate this function to indicators linked to sensors. The video cameras should provide a general view on the agricultural machine and/or tractor and area around. If it is possible the video cameras should be mounted in a way to show 360° perspective view on the field. Another option is a controlled camera(s) that can be turned to the point of interest. It can help in preventing or solving problems related to obstacles, animals or humans blocking the path of the autonomous machine.

- in comparison to video cameras, indicators linked to sensors can provide the same information in easy-to-get format. The indicators can achieve Level 2 or Level 3 of Situation Awareness. This feature should be considered during the interface design to reduce or exclude the necessity to pay full attention to the screens.

4.9 Future directions

The methodology used in the study was found to be acceptable in assessing the importance of the video footage for supervisory tasks. Future studies can use the same technique to determine the appropriateness of different interface designs for the remote supervision of an autonomous machine.

The interface design was not in the scope of the study and the influence of the design on the participants' performance has not been assessed. Future studies could investigate influence of the different design aspects, such as indicator type, layout, color, shape, and so on, on the participants' performance. It seems interesting to assess influence of the indicators designed to achieve at least Level 2 of situation awareness. The study can also take into account that more and more farmers use portable devices (smartphones, tablets) to control everyday farm activity.

Smaller screens and limited options to grab user attention create additional challenges for interface designers.

Another direction for future studies is the investigation of the influence of camera positioning on participant performance. The study might involve assessment of camera effectiveness depending on the camera type, position, direction, and/or tilt. It could be useful to develop recommendations for camera positioning depending on the type of agricultural machine.

5 Conclusion

The goal of the study was to determine importance of live video footage for remotely located supervisor of an autonomous agricultural machine. The experiment was conducted using AAMCI simulator. The importance of live video was estimated by measuring the participants' performance during the trials with and without video footage. The gaze distribution data were obtained using the Pupil Pro eye tracking system. Additionally, subjective opinions about the importance of the live video were collected.

The results of the study showed that live video is not an effective tool for sprayer problem detection. The participants' performance was poorer when the video footage was presented. During the course of the experiment, participant's attention gradually shifted to the screen with indicators. At the beginning of the experiment attention was equally distributed between the left (video) and the right (indicators) screens. At the end the ratio was 30/70 toward the right screen. That leads to conclusion that the indicators were the primary source of the information. At the same time analysis of the subjective responses showed that the participants felt more secure when the video footage was presented. More than ¾ of the participants indicated that the presence of the live video helped them to understand machine functions better.

The following recommendations might be considered by the autonomous machine control interface designers. First, the ability to watch live video should be included to the interface at least as an option. Second, the cameras should provide general view on a tractor, an implement, and surrounding environment. It should help in detection and avoiding obstacles during field operations.

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Appendix A. Education/Nursing Research Ethics Board Approval

UNIVERSITY OF MANITOBA | Research Ethics and Compliance

Human Ethics
208-194 Dafoe Road
Winnipeg, MB
Canada R3T 2N2
Phone +204-474-7122
Email: humanethics@umanitoba.ca

PROTOCOL APPROVAL

TO: **Ivan Panfilov** **(Advisor: Danny Mann)**
Principal Investigator

FROM: **Zana Lutfiyya, Chair**
Education/Nursing Research Ethics Board (ENREB)

Re: **Protocol #E2017:017 (HS20585)**
"Determining the importance of real-time visual information to the remote supervision of an autonomous agricultural machine"

Effective: March 16, 2017 **Expiry:** March 16, 2018

Education/Nursing Research Ethics Board (ENREB) has reviewed and approved the above research. ENREB is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.*

This approval is subject to the following conditions:

1. Approval is granted only for the research and purposes described in the application.
2. Any modification to the research must be submitted to ENREB for approval before implementation.
3. Any deviations to the research or adverse events must be submitted to ENREB as soon as possible.
4. This approval is valid for one year only and a Renewal Request must be submitted and approved by the above expiry date.
5. A Study Closure form must be submitted to ENREB when the research is complete or terminated.
6. The University of Manitoba may request to review research documentation from this project to demonstrate compliance with this approved protocol and the University of Manitoba *Ethics of Research Involving Humans*.

Funded Protocols:
- **Please mail/e-mail a copy of this Approval, identifying the related UM Project Number, to the Research Grants Officer in ORS.**

Research Ethics and Compliance is a part of the Office of the Vice-President (Research and International)
umanitoba.ca/research

Appendix B. Informed consent form

UNIVERSITY OF MANITOBA | Faculty of Agricultural and Food Sciences

Department of Biosystems Engineering
E2-376 EITC
Winnipeg MB R3T 5V6
CANADA
Tel: 204-474-6033
Fax: 204-474-7512

February 14, 2017

Determining the importance of real-time visual information to the remote supervision of an autonomous agricultural machine

Principal Investigator: Ivan Panfilov
Graduate Student, Department of Biosystems Engineering
University of Manitoba

panfiloi@myumanitoba.ca

Advisor: Dr. Danny Mann,
Ph.D., P.Eng
Professor & Head
Department of Biosystems Engineering
204-474-7149
Danny.Mann@umanitoba.ca

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the

research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

PURPOSE: We are interested in learning the effect of providing live video footage of machine operation on the situation awareness of the remotely-located supervisor.

DESCRIPTION: During the study, you will be asked to perform a supervisory job using a simulation of the autonomous machine supervisor workplace. The experimental session will include thirty trials. During half of the trials, information about machine status will be provided via indicators supplemented with video from cameras mounted on an agricultural machine. During the other half of the trials, you will receive information about machine status only via indicators. Each trial will last from 90 seconds to 150 seconds and will stop at random moment. After each trial you will be asked to describe the last state of the system by completing a paper form. Additionally you will be asked to indicate if you noticed system malfunctions at any time during the trial and what source of information (video footage or indicators) helped to detect the malfunction.

An eye tracking device will be used to record direction and duration of the gaze. You will be asked to wear a Pupil Pro Headset during all the trials. Following the experiment, you will be asked to complete a questionnaire and will be able to describe general impression about experiment and express subjective opinion about effect of providing live video footage on situation awareness of supervisor of autonomous agricultural machine.

You will be provided with two training sessions in order to familiarize with the simulator. The principal investigator will answer your questions if any. The whole procedure will take 1.5-2 hours to complete.

RISKS AND BENEFITS: There are minimal risks involved in the tasks you will perform. You are at risk of mental fatigue and some physical discomfort due to lack or minimal physical activity. We encourage you to take breaks after any of the trials during the experimental session whenever you feel tired.

Your participation in this study will help us examine the influence of providing live video footage on the situation awareness of the remotely-located supervisor. After the experiment you will have better understanding about how idea of autonomous agricultural machines might be implemented which might be beneficial for you of your job is connected or will be connected to agriculture.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. You will receive a $20 honorarium as thanks for donating your time.

CONFIDENTIALITY: Your information will be kept confidential. Once you begin the study a code number will refer to your results. All files containing identifying information will be stored in a locked cabinet separate from data with your code number. Only Ivan Panfilov and his advisor, Dr. Danny Mann, will have access to any lists that contain identifying information. Results will be presented at academic conferences, invited presentations, and published in peer-reviewed academic journals. This data contains no identifiable information and therefore your anonymity will be maintained. Five years after the publication of the results of the study, all paper and electronic files containing personal information will be destroyed by Dr. Mann.

VOLUNTARY CONSENT: If you do not wish to participate in the study, you are free to leave without consequence and we thank you for your consideration. You may withdraw at any point during the study in person, or before the study begins by e-mail. If you choose to withdraw from the study all personal information collected will be destroyed. The decision to withdraw from the study will not have penalties. You are free to refrain from answering any questions you prefer to omit, without prejudice or consequence.

DEBRIEFING AND FEEDBACK: If you would like to know more about research hypotheses debriefing will be provided with verbal feedback at the conclusion of the experiment.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at your research records to see that the research is being done in a safe and proper way.

This research has been approved by the Education/Nursing REB. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122. A copy of this consent form has been given to you to keep for your records and reference.

Participant Signature ____ Date _____________

Researcher Signature ____Date _____________

Please indicate if you would wish to receive a summary of the findings of this study:

___Yes ___No

Mode of delivery: e-mail/phone: __________

____

Appendix C. Questionnaire

Questionnaire

Which statement best describes the use of video footage to the supervisory task you were asked to complete?

- ☐ The presence of video footage increases my level of understanding of machine functions;
- ☐ The presence of video footage has no effect on my level of understanding of machine functions;
- ☐ The presence of video footage decreases my level of understanding of machine functions.

Video footage should be provided to the supervisor:

- ☐ All the time;
- ☐ Only when supervisor needs (on demand);
- ☐ Never.

Did you feel more confident about agricultural machine status when video footage was provided?

- ☐ Yes, I felt more confident;
- ☐ No, I felt less confident;
- ☐ No changes.

Was video footage helpful in detection of agricultural sprayer malfunctions?

- ☐ Yes;
- ☐ No.

If yes, please specify which malfunctions:

- ☐ Deviation from the path;
- ☐ Speed too low/high;
- ☐ Boom too low/high;
- ☐ Nozzle clogging;
- ☐ Low tank level.

Comments____
____
____
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Appendix D. The participants' comments about the experiment.

- It was hard to gauge speed, path, and boom height just from the video, due the cameras themselves were moving.

- Hard to see other malfunctions other than nozzle clogging on the left video screen

- I think display is more helpful to detect the fault that video footage

- Comparing video footage with the GUI, I believe video footage cannot help the sensual perception.

- The video footage provides limited understanding of machine functions when compare to the indicators. The supervisor may be affected by Attention Deficit Disorder (ADD) when both are combined in real life.

- I prefer watching "parameters screen" but footage videos still useful

- The video is good for double checking gauges but should not have the same priority. It should not be used for deviation. It would be nice if tractor position was displayed on mechanical motion board. So if you lost power the board would hold its position.

- I feel that the video footage was distracting. I felt more confident when it was only screen with indicators. Probably only one video might increase myconfidence.

- Video was helpful just to confirm the result of the detection of machine malfunctions from indicators but not very effective to detect the malfunctions.

- I felt that when both screens were on, there was too much information to juggle. My confidence in catching all errors went down. I also found random cards or people distracting.

- Deviation from the path was difficult to analyze on video. The right screen info was really easy to analyze and identify malfunctions.

- The video footage increased the awareness of the machine.

- Sound alarms could be more helpful. Video makes me more confident that sensors are operating right and serve as a confirmation of malfunction. Placing video closer to the position of sensor could improve results.

- Another video footage that shows the entire landscape to see accurately tractor location in reference to entire field. Although video footage decreased my confidence level, it helped identify of the malfunctions. It should be provided only when needed.

Appendix E. Order of the trials

Session		P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17
Session 1	1	2*	7	9	19	21	24	12	14	2	6	24	17	14	19	5	2	18
	2	5	17	7	24	12	12	24	5	14	24	9	21	21	12	19	9	5
	3	6	24	24	2	6	9	14	18	17	18	7	2	24	18	7	18	6
	4	7	2	12	6	2	7	19	2	12	9	2	5	2	6	2	5	24
	5	9	18	6	14	19	19	2	7	7	14	6	9	7	5	18	17	19
	6	12	5	19	5	17	14	6	9	6	17	18	24	19	2	21	12	12
	7	14	9	2	21	5	2	5	17	21	5	21	18	5	7	9	7	7
	8	17	19	21	9	18	5	9	6	18	7	19	19	12	24	24	6	2
	9	18	21	18	12	7	21	18	24	24	2	17	14	6	14	6	19	21
	10	19	12	5	18	9	18	17	12	19	12	5	6	9	17	17	14	14
	11	21	6	14	17	14	17	7	19	5	19	14	12	18	9	14	21	9
	12	24	14	17	7	24	6	21	21	9	21	12	7	17	21	12	24	17
Session 2	13	10	16	15	10	8	16	23	20	20	23	20	4	15	3	4	11	20
	14	15	3	3	20	22	11	4	11	1	13	4	10	13	20	20	10	13
	15	3	11	20	11	20	13	10	3	11	10	10	20	10	13	10	15	10
	16	11	20	16	1	3	8	16	15	23	20	16	22	8	1	23	4	8
	17	23	15	8	3	1	1	11	10	16	1	15	8	20	10	11	8	23
	18	22	10	10	15	10	20	8	23	22	3	13	3	3	8	3	13	11
	19	13	23	22	8	16	15	13	13	3	15	1	1	22	16	15	20	22
	20	20	4	11	22	11	4	22	1	13	16	23	13	1	4	16	1	1
	21	16	1	4	23	4	23	20	16	15	22	22	11	11	15	8	23	15
	22	1	8	13	16	15	3	1	8	4	4	3	23	23	11	13	16	4
	23	4	13	1	13	23	22	15	22	8	8	8	15	4	22	1	3	16
	24	8	22	23	4	13	10	3	4	10	11	11	16	16	23	22	22	3

* Case 1 trials are indicated with red

Appendix F. The participants' performance data

Trial #	Problem	Correct answer		P01					P02					P03					P04					P05					P06					P07					P08					P09					P10					P11					P12					P13					P14					P15					P16					P17				
		I	C	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4	I	C1	C2	C3	C4
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	Pump pressure	x		x					x					x																									x					x					x					x					x					x															x					x				
	Nozzle	x	x	x								x		x					x					x								x		x					x								x		x					x					x					x					x					x					x					x				
	Deviation	x	x	x					x					x					x										x					x					x					x					x					x					x					x										x					x					x				
12	Speed	x	x	x					x					x					x					x					x					x					x					x					x					x					x															x					x					x				
	RPM	x		x					x					x					x					x					x					x					x					x					x					x					x					x					x					x					x					x				
	Pump pressure	x							x					x					x					x										x					x					x					x					x					x					x										x										x				
	Nozzle		x																			x																																																		x		x															
	Deviation		x																																																																																										

13 RPM	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x
Temperature	x	x	x	x	x	x				x	x	x	x	x		x		x
Boom height	x		x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
14 Speed	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
App rate	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x
Boom height	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pump pressure	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
15 Speed	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
RPM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Boom height	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Nozzle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
16 Speed	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
App rate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pump pressure	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Nozzle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
17 Temperature	x	x	x	x	x	x		x		x	x	x		x	x	x	x	x
App rate	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Boom height	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Deviation	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
18 Temperature	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x
Boom height	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pump pressure	x		x	x	x		x		x	x	x	x	x	x	x	x	x	x
Nozzle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
19 RPM	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x
Boom height	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pump pressure	x	x	x	x	x	x			x	x	x				x	x	x	x
Nozzle	x	x	x	x		x	x	x	x	x	x	x	x	x	x		x	x
Deviation	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	
20 Speed	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Fuel	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Tank	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Deviation	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
21 Speed	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x
Temperature	x		x	x	x	x		x		x	x	x	x	x		x	x	
App rate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Nozzle	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x
22 RPM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
App rate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Deviation	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
23 App rate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Boom height	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x
Pump pressure	x	x	x	x	x	x		x	x	x	x	x	x	x		x	x	
Nozzle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Deviation	x	x	x	x	x	x		x	x	x	x	x	x	x		x	x	x
24 Speed	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
RPM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Pump pressure	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x

I – indicator; C – Camera image; C1 – Top left camera; C2 – Top right camera; C3 – Bottom left camera; C4 – Bottom right camera

Appendix G. Gaze distribution data

Participant #		Trial # 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
P01	L*	*47.6*	*46.8*	*49.9*	*48.6*	*59.1*	*49.4*	*38.4*	*53.4*	*42.2*	*41.2*	*54.2*	*35.2*	*28.4*	*39.9*	*26.6*
	R	*52.4*	*53.2*	*50.1*	*51.4*	*40.9*	*50.6*	*61.6*	*46.7*	*57.8*	*58.8*	*45.8*	*64.8*	*71.6*	*60.1*	*73.4*
P02	L	*29.2*	*31.6*	*35.9*	*23.4*	*34.3*	*37.3*	*30.9*	*35.4*	*34.6*	*38.4*	*27.6*	*34.3*	*28.4*	*33.2*	*33.1*
	R	*70.9*	*68.4*	*64.2*	*76.7*	*65.7*	*62.7*	*30.9*	*64.7*	*65.4*	*61.6*	*72.4*	*65.7*	*71.6*	*66.8*	*66.9*
P03	L	*23.4*	*33.2*	*26.0*	*33.4*	*29.3*	*26.5*	*38.1*	*31.3*	*31.8*	*33.4*	*24.3*	*36.1*	*20.1*	*21.2*	*23.5*
	R	*76.7*	*66.8*	*74.0*	*66.6*	*70.7*	*73.5*	*61.9*	*68.7*	*68.2*	*66.6*	*75.7*	*63.9*	*80.0*	*78.8*	*76.5*
P04	L	39.1	19.4	23.4	39.8	37.3	31.2	20.6	29.7	26.0	16.5	27.9	32.0	42.8	25.4	27.0
	R	60.9	80.6	76.6	60.2	62.7	68.8	79.4	70.3	74.0	83.5	72.1	68.0	57.2	74.6	73.0
P05	L	*19.4*	49.6	61.5	43.8	41.8	37.9	35.5	36.6	52.2	29.8	47.1	29.6	30.5	22.9	17.3
	R	*80.6*	50.4	38.5	56.2	58.2	62.1	64.5	63.4	47.8	70.2	52.9	70.4	69.5	77.1	82.7
P06	L	40.5	38.7	45.3	28.8	33.6	43.4	42.4	45.3	43.1	33.0	31.4	42.5	23.6	52.6	34.6
	R	59.5	61.3	54.7	71.2	66.4	56.6	57.6	54.7	56.9	67.0	68.6	57.6	76.4	47.4	65.4
P07	L	46.3	52.3	50.1	45.7	60.3	52.1	47.7	55.1	36.5	48.3	44.6	40.4	29.9	38.9	31.2
	R	53.7	47.8	49.9	54.3	39.7	47.9	52.3	44.9	63.5	51.7	55.4	59.6	70.1	61.1	68.8
P08	L	50.4	28.6	27.0	18.7	39.1	30.7	33.7	47.2	34.0	27.1	33.2	26.4	24.5	26.9	27.7
	R	49.6	71.4	73.1	81.3	60.9	69.3	66.3	52.9	66.0	72.9	66.8	73.6	75.5	73.1	72.4
P09	L	58.3	30.0	27.7	19.3	27.7	21.1	42.9	24.4	20.5	27.1	29.7	28.9	22.8	21.4	14.0
	R	41.7	70.0	72.3	80.7	72.3	78.9	57.1	75.6	79.5	72.9	70.3	71.1	77.2	78.6	86.0
P10	L	54.1	44.5	47.9	42.0	41.6	45.4	37.2	44.7	45.1	49.5	42.0	46.9	46.4	32.2	36.4
	R	46.0	55.5	52.1	58.0	58.4	54.6	62.8	55.3	54.9	50.5	58.0	53.1	53.6	67.9	63.6
P11	L	55.3	34.3	23.8	26.6	30.1	19.6	24.0	31.9	27.1	21.3	23.4	16.2	38.2	34.5	37.3
	R	44.7	65.7	76.3	73.4	70.0	80.4	76.0	68.1	72.9	78.7	76.6	83.8	61.8	65.5	62.7
P12	L	*53.5*	*41.6*	51.2	42.9	41.1	38.2	31.4	24.2	32.9	25.7	27.4	30.2	34.5	30.1	23.8
	R	*46.5*	*58.4*	48.8	57.1	58.9	61.8	68.6	75.8	67.1	74.3	72.7	69.8	65.5	70.0	76.2
P13	L	54.5	60.9	51.1	*54.1*	*40.6*	*48.2*	*58.9*	*49.8*	*45.9*	*40.7*	36.5	30.6	41.9	36.7	41.0
	R	45.5	39.2	48.9	*45.9*	*59.4*	*51.8*	*41.1*	*50.2*	*54.1*	*59.3*	63.5	69.4	58.2	63.3	59.0
P14	L	77.1	64.3	45.9	36.5	61.8	36.2	64.8	51.6	20.2	41.9	41.6	43.4	38.5	59.2	44.2
	R	22.9	35.7	54.2	63.5	38.3	63.8	35.3	48.4	79.8	58.1	58.4	56.6	61.5	40.8	55.8
P15	L	45.9	47.2	51.0	47.5	42.4	36.4	34.4	34.4	23.3	35.6	28.2	26.7	35.9	20.0	37.1
	R	54.1	52.8	49.0	52.5	57.6	63.7	65.6	65.6	76.7	64.5	71.8	73.3	64.1	80.0	62.9
P16	L	40.3	57.8	24.5	50.8	51.7	27.7	28.8	16.2	21.9	22.0	18.2	20.2	24.7	32.1	32.5
	R	59.7	42.2	75.5	49.2	48.3	72.4	71.2	83.8	78.1	78.0	81.8	79.8	75.4	67.9	67.5
P17	L	84.6	64.4	45.6	39.2	34.5	29.9	30.0	26.7	31.8	33.8	31.7	44.3	43.2	33.4	31.2
	R	15.4	35.6	54.4	60.8	65.5	70.2	70.0	73.3	68.2	66.2	68.3	55.7	56.8	66.6	68.8
Avg	L	48.2	43.8	40.5	37.7	41.5	35.9	37.6	37.5	33.5	33.3	33.5	33.2	32.6	33.0	30.5
		51.8	56.2	59.5	62.3	58.5	64.1	60.1	62.5	66.5	66.7	66.5	66.8	67.4	67.0	69.5

* L and R stand for left and right screens respectively