Automation and drivers’ performance in agricultural semi-autonomous vehicles

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ABSTRACT There are an increasing number of automated systems that have been introduced into agricultural vehicles to enhance their work performance. Studies have shown implications of automation support on the operators’ performance in various domains such as air-traffic control, nuclear power plant control and car driving. In this pilot study, the effect of steering automation and type of automation aid for implement monitoring and control was investigated using a tractor air-seeder system as a case study. Experiments were conducted using the tractor air seeder driving simulator (TAS-DS) located in the Agricultural Ergonomics Laboratory at the University of Manitoba. Study participants were university students. Results showed that, in most of the automation support modes, the drivers’ situation awareness stayed at over moderate level and the experienced mental workload was close to a moderate level. The simulator study revealed no steering automation effect on drivers’ situation awareness and workload. Implement control and monitoring automation, however, showed significant effect on both situation awareness and mental workload.

Keywords: Machinery systems, automation, situation awareness, mental workload.

INTRODUCTION In recent years, there has been a dramatic development in automated systems and they have been implemented in almost every aspect of our lives. Agricultural vehicles have been an important target for automated systems in order to increase the productivity that can be
achieved when using these vehicles (Edan et al., 2009). The wide variety and diversity of agricultural vehicles throughout the world creates many scenarios of automation application. A modern tractor air-seeder system, for instance, has numerous automatic features such as automatic steering, control of working depth, travel speed, seed and fertilizer application rate and empty tank warning system. With such automated systems, modern farmers are interacting with semi-autonomous agricultural vehicles.

With the current state of automation in various domains, the involvement of the human operator in the work loop is unavoidable. Depending on the level and type of automation, the involvement can embrace different types of physical and mental tasks for the operator. To ensure a high performance and safety in this situation, constant feedback from both companions (man and machine) will be necessary. It is stated that the current level of automation in industry does not provide adequate feedback to the human operator, so automation can cause human error when the situations exceed the capabilities of the automatic equipment (Norman, 1990). Unbalanced workload, loss of situational awareness (Endsley and Kaber, 1999, Cummings, 2004, Stanton and Young, 2005, Walker et al., 2008), vigilance decrements (Parasuraman, 1986, Finomore et al., 2009), complacency (Kaber and Endsley, 2004), and skill degradation (Billings, 1996) are some of the consequences of automation that can cause human errors in situations lacking proper feedback. Considering the human machine collaboration in agricultural vehicles, a human factors perspective is needed to ensure the safe and efficient operability of agricultural machines (Lang et al., 2009).

Mental workload is an important subject of human factor studies. Mental workload reflects perceptual and cognitive demands of tasks on the limited mental resources (Di Stasi et al., 2013). In fact, workload has been used to explain the interaction between the task and the operator who is doing the task (Prinzel et al., 2003a). There have been many studies on operators’ mental workload in human-machine systems (Baldwin et al., 2004, Cantin et al., 2009, Pauzie, 2008a, De Waard, 1996, Young and Stanton, 1997), and accordingly many methods have been developed. Three categories can be assumed for mental workload measurements: subjective, physiological, and task performance measures.

Subjective reports have been used for assessment of operators’ mental workload (Laux and Plott, 2007). An example of a subjective workload assessment tool is the NASA-Task Load Index (NASA-TLX) rating scale which was originally designed to assess pilot workload in the aviation domain (Pauzie, 2008a). The Driving Activity Load Index (DALI) is a revised version of the NASA TLX for the driving task (Pauzie, 2008b). Pauzie (2008b) developed and used this technique to assess the usability of mobile phones and guidance/navigation systems for drivers.

Some physiological measures have shown to be valuable measures of operators’ workload. The three most promising physiological measures of mental workload are the electroencephalogram (EEG), event-related potential (ERP), and heart-rate variability (HRV) physiological signal (Kramer et al., 1996, Prinzel et al., 2003b). Experiments by Prinzel et al. (2003b) confirmed the usefulness of these three measures for adaptive automation design. A study by Schrauf et al. (2011) confirmed the usefulness of EEG and HRV for real road driving experiments. Another study by Dey and Mann (2010) using HRV measurement showed that the mental workload of an agricultural sprayer was increased when they were driving with a light-bar compared to an auto-steer navigation device.

Measures of task performance include techniques for direct measurement of operators’ behavior while performing task. In the automotive domain, the goal is direct registration of the operator’s capability to perform the driving task at an acceptable level (Brookhuis et al., 2009). This can be done directly by measuring primary task performance (i.e., vehicle handling tasks such steering and car following, or indirectly by means of secondary tasks, like responding to a cellphone). In case of
primary task performance, the numbers of human errors, performance speed or reaction time can be used as performance measures in laboratory tasks.

In the past two decades, there have been many studies on situation awareness, and the term situation awareness has become a vernacular to human factors researchers (Wickens, 2008). It was mentioned that situation awareness is an operator’s dynamic understanding of ‘what is going on’ (Salmon et al., 2009). In human-machine systems, the situation dynamically changes by time so there will be some times that the operator does not get sufficient feedback. This happens when automation takes over the situation, and as a result, the operator’s situation understanding deteriorates (Bye et al., 1999). Low situation understanding means lower system performance. This is the major concern in designing a human-machine system. There are numerous methods for measurement of situation awareness. Situation Awareness Rating Technique (SART) is a widely used subjective report technique for the measurement of situation awareness.

Although there are many studies on driving tasks of on-road vehicles, driving off-road vehicles and especially agricultural vehicles demand specific research. This pilot study sought to examine the effect of task automation in agricultural vehicles on drivers’ mental workload and situation awareness. In this research, a tractor air-seeder system was considered as a case study. The tractor driving simulator located in the Agricultural Ergonomics Lab, Department of Biosystems Engineering, University of Manitoba was used for the experiments. In this study, we used a method to incorporate three mental workload and one situation awareness measures.

**METHODOLOGY** Based on the literature, two independent variables were considered in the study: 1) taskload and 2) the automation support. The taskload variable referred to the steering task and included two levels: manual steering and automatic steering. Manual steering or high taskload context meant that operators were responsible for steering throughout the field. In automatic steering mode or low taskload context, on the other hand, an auto-steer system was engaged to perform the steering task.

The second variable was the automation support which provided different levels and types of automation support during monitoring and control of the implement (air-seeder). The monitoring and control of the air-seeder included a supervisory task in which any errors needed to be eliminated immediately after their occurrence. The levels and types of automation support were defined based on the instructions provided by Parasuraman et al (2000) and included five different settings of manual (no support), information acquisition, information analysis, decision and action selection, and action implementation supports.

In manual setting, no visual support was added to the previous information display configuration of the simulator, designed by Karimi et al. (2011). For information acquisition mode, the computer was responsible for detecting errors and highlighting them, leaving the rest of the task to the operator. In information analysis mode, the computer analyzed the data and made predictions. In this mode, a warning message was provided prior to error occurrence. Operators needed to interpret the message and perform the necessary action. Decision and action selection mode was a condition in which the computer suggested a proper action, requiring the operator to implement the action. And finally, the action implementation mode reflected the highest level of automation in this study; the computer performed all of the information processing functions and only informed the operator after performing a task.

Dependent variables of this study included operators’ mental workload and situation awareness, heart rate variability, reaction time, and reaction accuracy. DALI and SART were used as subjective measures of mental workload and situation awareness. Data regarding operators’ reaction time and accuracy were collected directly through the simulator code. In addition, a heart rate monitor (Polar™ S810, Polar Electro Inc., Lake Success, NY) was used to measure drivers’ HRV.
**Experimental design and analysis** The experiment needed human subjects to participate in the study. This was considered as a blocking factor as the human acted as random effects. Another blocking factor was the driving period. Having five driving conditions might show learning effect and bias on data. To avoid this learning effect and to accommodate the limited number of subjects (considering the number of treatments), a repeated Latin square design was used. The preliminary experiment included two Latin squares, sharing same columns (driving period), with five rows (subjects). Subjects of the experiments were 10 university students ranging in age from 20 to 35 years (M = 26.5, SD = 5.38) who volunteered for participation in the study. They were randomly assigned to two groups of five. For each group, as the between-subject design, only one task-load condition (manual or auto-steer) was assigned. Automation support was assumed in the form of a within-subject design and was assigned to each participant. Data were analyzed using SAS statistical software (SAS Institute Inc., Cary, North Carolina, USA).

**Procedure** The experiment needed approximately 2 h of participation. Participants first received explanation of the test procedure and were provided with necessary instructions upon arrival to the Lab. They were required to sign a consent letter containing such information. They then completed a training session where they learned to drive the simulator and monitor and control the implement parameters. Afterwards, they completed the five experimental driving scenarios, each 12 min in duration. At the end of each driving period, participants answered paper-based queries of SART and DALI. During the experimental driving periods, real-time HRV data were recorded. At the end of the experiment, each subject received an honorarium of 40$ for volunteering in the experiment.

**RESULTS** A promising method for measuring drivers’ mental workload is the DALI subjective rating scale. Depending on the driving or test condition, up to seven mental workload factors can be measured using DALI, including global attention demand, visual demand, auditory demand, tactile demand, stress, temporal demand, and interference. If any of these factors is not applicable, it can be simply eliminated from the questionnaire. For example, for a trial without any vibrations, tactile demand has no meaning and it can be removed. In this study, two factors (i.e., auditory and tactile demands) were ignored. Tractor noise was incorporated in the simulator, but no audio file was assigned to the controllers. The simulator also does not have any vibration system. Only five factors were considered in the analysis. Figure 1 shows the means of DALI parameters. In all of the cases, manual steering resulted in higher global mental workload and higher values for its components, however, a table of differences of least square means showed no taskload effect on any of the DALI parameters. Automation effect was found on all of the parameters excluding interference. The Interaction effect was only found on attention demand.

![Figure 1. Mental workload parameters in different taskload levels.](image-url)
Looking at the global workload results (Figure 2a), there is a significant difference between the automation support levels in terms of subjective assessment of workload by the operators. Having the lowest mean value (6.0 ± 1.0), the Action support mode yielded the lowest mental workload. Decision support mode (8.3 ± 1.0) also had a different effect on mental workload compared to the Manual (11.0 ± 1.0) and Information Acquisition support (10.2 ± 1.0) modes.

For attention demand (Figure 2b), action implementation support (5.6 ± 1.3) had different effect compared to the other automation aids. Manual (13.1 ± 1.3) and decision support (10.0 ± 1.3) modes also showed significantly different effects on attention demand. In auto-steer mode (low taskload), manual and information acquisition support had different effects compared to decision and action supports. In fact, manual and information acquisition support resulted in over moderate global attention demand whereas action and decision support caused lower demands. In manual steering mode only action support showed different effect by significantly reducing the demand.

In the case of visual demand (Figure 2c), similar to attention demand, action support (7.6 ± 1.6) significantly decreased the demand. The remaining automation types resulted in moderate to above moderate values. All of the automation types imposed below a moderate level of stress on operators (Figure 2d). Again this was action support (3.6 ± 1.4) which caused the lowest stress. Manual (8.4 ± 1.4) and decision support (5.9 ± 1.4) also showed significantly different effects compared with each other. Statistically, manual (8.9 ± 1.6), information acquisition (8.4 ± 1.6) and analysis (8.7 ± 1.6) supports had similar effects on operators temporal demand (Figure 2e). Action support caused the lowest temporal demand with the least square mean of 4.1 ± 1.6. This was not significantly different from the effect of decision support (6.5 ± 1.6), but the rest of automation types.

Figure 2. Mental workload parameters in different automation support modes: manual (Man), information acquisition (Acq), information analysis (Ana), decision making (Dec), and action implementation (Act).
Drivers’ reaction time and accuracy of their actions can be considered as an indicator of their mental workload; in this study, a reaction time was defined as the period of time between the emergence of an error and the time that a driver started to make an adjustment. If the adjustment was performed prior to the emergence of the error, it would be considered as a zero reaction time, but would also be considered as an error; subjects were specifically asked to adjust parameters when an error appeared. Ignoring an error, adjustment of a wrong parameter, and adjusting a correct parameter but in a wrong direction were considered as drivers’ inaccurate actions.

The tractor driving simulator was able to record real-time drivers’ course of action. Data from the simulator were reviewed separately for each participant in order to calculate his/her performance parameters. Results showed that driving with the auto-steer system caused higher average reaction time compared to the manual steering mode (2.84 ± 0.42 s vs. 2.09 ± 0.42 s). By contrast, the number of failures was higher in manual steering mode (27 vs. 44).

Figure 3 shows means of reaction time and accuracy in different taskload and automation conditions. Despite the lower values of automatic steering mode, the statistical analysis showed no taskload effect on reaction time and accuracy. Automation support presented significant effects. It was hypothesized that as the level of automation support was increased, reaction time would decrease. The observed results, however, showed inconsistencies; no differences were found among manual, acquisition and decision support modes. Differences of least square means indicated that information analysis (1.69 ± 0.41) and action implementation (0.71 ± 0.41) supports significantly reduced the reaction time. In the case of accuracy, automation caused similar number of errors in manual (2.0 ± 0.58), acquisition (1.5 ± 0.58), analysis (2.2 ± 0.58) and decision support modes (1.2 ± 0.58), unlike the action mode with no errors. No interaction effects were found between taskload and automation support for both parameters.

**HRV** The variation in the time interval between heartbeats is known as HRV. It has been reported that the 0.1 Hz component of HRV follows a decreasing trend as mental load increases (Ramon et al., 2008), so it has been used in different studies to assess mental workload demands. HRV is best characterized by R-R interval. R-R interval refers to the distance between the highest wave (R wave) of a heartbeat to the highest wave (R) of the next heartbeat.

In this study, the HRV was measured to declare its sensitivity to subtle changes of driving condition in a tractor driving simulator. The HRV parameters used in this study included the average R-R interval (mean RR), standard deviation of R-R interval (SDRR), percentage of beats that differ by
more than 50 ms (pNN50) and absolute low frequency (LF) power (0.1 Hz component, measured between 0.07 - 0.14 Hz). 10 min of HRV data (out of 12 min) from each driving period were used in the analysis.

The results did not show any significant effects of taskload and automation support on participants HRV parameters. This result could be due to two reasons: first, the insensitivity of the measure in the tractor driving simulator, and second, the experimental condition. It is stated that individuals HRV vary due to age, genetic composition, and environment (Taelman et al., 2008). Subjects’ age, in this study, varied from 20 to 35; that is a wide range in case of HRV. Besides, they were from different ethnicities; two Caucasian, two Hispanic, five Asian, and one African participated in the experiment. Another factor that affects HRV is the gender of subjects. In the experiment, there was a female participant in addition to nine male participants, so 10% of the results came from a different gender. Participants also differed in terms of car and tractor driving experience. Participants’ car driving experience ranged from less than 1 yr to 15 yr. Five participants did not have any tractor driving experience, while two of the participants had over 10 yr of tractor driving experience.

SART rating scale can measure up to 10 dimensions of drivers’ situation awareness. These dimensions can be categorized in three distinctive groups: demand on attentional resources, supply of attentional resources and understanding. Demand on attentional resources includes questions regarding instability, complexity and variability of a situation. Supply of attentional resources reflects arousal, concentration, division and spare mental resources in dealing with a situation. And finally, understanding of a situation depends on the quality and quantity of the provided information as well as familiarity with a situation. Values for each of these categories can be derived by getting the average of responses to questions included in such categories. Finally the combined rate for situation awareness can be inferred by deducting the average demand from the sum of average understanding and supply.

In statistical analysis of the data, scores of SART-combined and its three components were studied. As shown in Figure 4, auto-steer mode (low taskload context) resulted in slightly higher situation awareness of drivers. Both task-load conditions imposed almost equal demand on attentional resources and understanding, although lower task-load allowed higher values for supplying of attentional resources. The analysis of variance revealed no task-load, automation and taskload-automation interaction effect on SART-combined. Thus, adding the steering task to the supervisory task neither increased nor decreased operators’ situation awareness. This can be due to routineness of steering task in a straight line in a field while seeding.

![Figure 4. Total Situation awareness and its components in high (manual steering) and low (automatic steering) taskload modes.](image-url)
For three dimensions of SART, same as SART - combined, no taskload and taskload- automation interaction effects were found. Automation support effect was found on two dimensions of demand and supply. According to the table of differences of least square means, in case of demand on attentional resources, for all of the observations, action implementation had different effect compared to the rest of the automation support settings. Looking at the means of demand (Figure 5), action implementation reduced demand on attentional resources by 13.5% compared to the means of the other automation aids. Similar results were found in case of supply of attentional resources where the action implementation resulted in 17.5% less values. Based on the SART-combined formula, reduction in demand would be a desirable outcome while reduction in supply of attentional resources would not. Overall, the action automation appears to not be the best choice if the situation awareness of the drivers needs to stand in higher levels, hence drivers need to be involved in the task loop to some extent.

![Figure 5. Situation awareness components in five automation support conditions: manual (Man), information acquisition (Acq), information analysis (Ana), decision making (Dec), and action implementation (Act).](image)

**CONCLUSION** A preliminary experiment was performed to assess the effect of steering task and implement control and monitoring task automation on the tractor driver's mental workload and situation awareness. Multiple human factors measures showed a greater effect of the implement monitoring and control automation on both mental workload and situation awareness. Subjective and task performance measures showed sensitivity to the changes in the driving conditions, while the measure of HRV was not able to differentiate them.

Based on the results, adding a physical task (manual steering) to a supervisory task (implement control and monitoring), caused slightly lower situation awareness and higher mental workload, but statistically did not show any significantly different effect. Automation of the implement control and monitoring had a significant effect on drivers’ performance issues. Involvement of the operator in the task loop seemed to be a better solution if a higher situation awareness and medium levels of workload would be desirable.

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