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HRI usability evaluation of interaction modes for a teleoperated agricultural robotic sprayer

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ABSTRACT

Teleoperation of an agricultural robotic system requires effective and efficient human-robot interaction. This paper investigates the usability of different interaction modes for agricultural robot teleoperation. Specifically, we examined the overall influence of two types of output devices (PC screen, head mounted display), two types of peripheral vision support mechanisms (single view, multiple views), and two types of control input devices (PC keyboard, PS3 gamepad) on observed and perceived usability of a teleoperated agricultural sprayer. A modular user interface for teleoperating an agricultural robot sprayer was constructed and field-tested. Evaluation included eight interaction modes: the different combinations of the 3 factors. Thirty representative participants used each interaction mode to navigate the robot along a vineyard and spray grape clusters based on a $2 \times 2 \times 2$ repeated measures experimental design. Objective metrics of the effectiveness and efficiency of the human-robot collaboration were collected. Participants also completed questionnaires related to their user experience with the system in each interaction mode. Results show that the most important factor for human-robot interface usability is the number and placement of views. The type of robot control input device was also a significant factor in certain dependents, whereas the effect of the screen output type was only significant on the participants' perceived workload index. Specific recommendations for mobile field robot teleoperation to improve HRI awareness for the agricultural spraying task are presented.

1. Introduction

Research on robotics in agriculture has been an active topic since the early 1980s with focus on development of autonomous robotic systems for different applications (Eaton, 2009; Edan et al., 2009; Garcia-Alegre et al., 2001; Hollingum, 1999; Isaacs, 1986; Li et al., 2009) such as fruit harvesting (Bac et al., 2014), spraying (Moreno et al., 2014; Oberti et al., 2013; Ogawa et al., 2006), and weeding (Lee et al., 1999; Slaughter et al., 2008). However, these autonomous systems have limited performance (Bac et al., 2014).

Agricultural robots operate in a dynamic, complicated, rough terrain, and in complex real world environments, as opposed to industrial robots which operate in fully controlled and set environments (Edan et al., 2009). An agricultural robot must identify and handle a variety of objects (e.g. fruits, weeds, branches), which are often obscured from leaves, daylight (or shadow), other branches or nearby fruits, or are just hard to reach (Isaacs, 1986). The shape and color of these objects is also non-standard and varies even on the same plant (Gongal et al., 2015; Kapach et al., 2012), making it more difficult to identify and pick the right target (Edan, 1999). The navigation of the robots in the rough and uneven terrain, in combination with various obstacles that can appear anywhere, such as fallen tree branches, big rocks, or even watering systems, makes the mobility of the agricultural robot even more challenging (Edan, 1995). Semi-autonomous robots share control with the

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human and have been found to increase detection of targets by 4% compared to a human operator alone (Bechar and Edan, 2003), and by 14% compared to a fully autonomous robot.

However, usable human-robot interactions must be designed to support operators to perform complex tasks (Eliav et al., 2011; Wilde and Walter, 2010). Usability refers to whether a system can be used with effectiveness, efficiency, and satisfaction with which specified users achieve specified goals in a particular context of use (ISO, 1998). Clarkson and Arkin (2007) declared that effective robotic interfaces should be designed similarly to effective devices, such as door handles (Norman, 1988) or software (Molich and Nielsen, 1990). Telerobotics allow the farmer to remotely interact with the robot in the field, thus leveraging the farmer's knowledge, and also protecting the farmer from the adverse conditions of working in the field.

In the case of AgriRobot, a teleoperated robotic sprayer (Adamides, 2016), a human farmer 'behind' the robot directs the agricultural work from a safe distance and in comfortable conditions, receiving data from the robot's sensors and cameras. Multimodal controls and displays have a great potential in robotic teleoperation tasks (Chen et al., 2007). However, several issues should be considered when designing user interfaces (UIs) for these tasks (Monferrer and Bonyuet, 2002). These include customized reference data, such as the affordance to point and select in the area where the task is taking place (e.g. mark and spray the grape clusters of a vineyard), and attractive data presentation (e.g. inform the user about potential obstacles). Additionally, there are still open questions about the usability of devices to control an agricultural mobile field robot, such as how many cameras and where they should be placed in order to provide sufficient awareness. There are also questions related to the control and feedback mechanisms to the robot operator (i.e. type of input controllers and output devices).

Robots interact dynamically with the physical world based on a "world model" with perceptual and sensor systems used for input. Chen et al. (2007) explains that, poor perception has a detrimental effect on situational awareness, especially in teleoperating environments in which the human perception is often compromised because of the physical environment (e.g. sunlight, shading). The use of remote site cameras compensates for improving the operator's situational awareness (Endsley, 1995). The provision of real-time visual images from the remote site is a means to reassure the operator that the task is progressing as planned, thus reducing the gulf of evaluation (Norman, 1988). Chen et al. (2007) reported the challenges that an operator faces while interacting with a robot located at a remote site. The situation awareness (denoted SA) of the operator may be reduced and this has negative consequences on the effectiveness of the mission (Drury et al., 2007; Endsley, 1988; Wilde and Walter, 2010). Teleoperation can also be a challenge due to the increased cognitive load of the user caused by the constant change of view/mode and the latency due to technological limitations (Drury et al., 2007). To improve SA, multimodal interactive user interfaces (e.g., tactile, aural, auditory, and visual) and controls (e.g., 3D-map, video-feedback) may be incorporated (Drury et al., 2007).

Limited field of view influences the effectiveness of remote driving since drivers may have more difficulty in judging the speed of the vehicle, time-to-collision, perception of objects, location of obstacles, and the start of a sharp curve (Chen et al. (2007). Peripheral vision is important for lane keeping and lateral control (Jie et al., 2009). Wider field of view is particularly useful in tactical driving tasks when navigating in unfamiliar terrain (Ricks et al., 2004), minimizes distortion and enables to easier cope with the difficulties of locating objects in the field of view of a teleoperated robot (Casper and Murphy (2003); (Eliav et al., 2011). In order to successfully navigate in remote environment, the operator of the robot needs to have a good sense of orientation both globally and locally. For robots with extended manipulators (e.g. sprayer wand), cameras may be placed on top of the end-effector (e.g. sprayer nozzle) in order to capture the remote scene egocentrically or on the body of the robot to provide for exocentric view of the end-effector (Rastogi, 1996).

Martins and Ventura (2009) proposed a visualization/control system of their search and rescue RAPOSA robot, based on a Head Mounted Display (HMD). They concluded that the user's depth perception and situational awareness improved significantly when using the HMD. Moreover, their efficiency and effectiveness was improved: users were able to reduce the operation time by 14% and successfully identify more objects when using the HMD. By contrast, Lichtenstern et al. (2013) reported several users' inconveniences with HMD and higher overall task load index, which however tended to decrease over the course of time.

Randelli et al. (2011) conducted an experiment to evaluate three control input interfaces for robot teleoperation: the Wiimote controller, a joypad implemented on a Wiimote device, and a PC keyboard. They found that the least effective interface was the joypad. The Wiimote controller and the PC keyboard were significantly better in terms of collisions, compared to the joypad, while the Wiimote was not statistically significant with respect to the keyboard. Participants' of the experiment reported that "the PC keyboard was the best interface for controlling the robot in narrow spaces, whilst the Wiimote was too reactive for hard terrain difficulty conditions". Randelli et al. (2011) conclude that tangible user interfaces such as the Wiimote are too sensitive for much cluttered areas. Similarly, Velasco et al. (2015), evaluated three approaches to control teleoperated mobile robots: the PS3 gamepad, a PC keyboard, and a mobile phone interface. They conclude that the PS3 controller was adequate for handling the mobile robot, the keyboard was efficient, while the phone interface was the most intuitive.

Eliav et al. (2011) examined two innovative methods to control a Pioneer 2DX mobile robot: a touch screen and using hand gestures. They found the touch screen to be "superior in terms of both objective performance and its perceived usability", while hand gestures were perceived as more complex. Guo and Sharlin (2008) evaluated an interaction technique which utilizes simple generic 3D tangible user interfaces (using the Nintendo Wiimote and Nunchuk) to capture human arm and hand gesture input for human-robot interaction. They conducted a comparative user study which compared the Wiimote/Nunchuk interface with a traditional input device (i.e. keypad) in terms of speed and accuracy. The results of their experiment provided some evidence that a gesture input scheme with tangible user interfaces could outperform a button-pressing input design for certain HRI tasks.

Murakami et al. (2008), developed a system for teleoperation of agricultural vehicles. The developed user interface provided a map using Google Maps, an indicator of the vehicle location in the field, and included an omnidirectional camera to give feedback to the operator about obstacles around the robotic vehicle and about its activities.

In this paper, the focus is on semi-autonomous operation, which implies that the robot to some degree operates autonomously, however for some operations it requires human intervention. The human operator is not co-located with the robot and therefore some kind of a user interface is needed to enable the user to interact with the robot. The objective of this research is to study the design and evaluation aspects of human-robot interaction devices for semi-autonomous agricultural spraying robots. The research is applied for the specific task of vineyard spraying.

Specifically, we examined the overall influence of two different types of output devices, two different types of peripheral vision support mechanisms, and two different types of control input devices on observed and perceived usability of a teleoperated agricultural sprayer. To this end, we performed a series of field experiments in which participants were asked to guide an agricultural robot along vineyard rows while avoiding obstacles, and detecting and targeting spray clusters. Our hypotheses per examined factor were the following:

1 Screen output

Null hypothesis: *Participant performance (grapes sprayed, collision avoidance, completion time) and self-reported measures (system usability score, overall task load index, presence score) will not differ in the PC screen and head mounted display conditions.*

2 Number of views

Null hypothesis: *Participant performance (grapes sprayed, collision avoidance, completion time) and self-reported measures (system usability score, overall task load index, presence score) will not differ under the single view and multiple views conditions.*

3 Robot control input

Null hypothesis: *Participant performance (grapes sprayed, collision avoidance, completion time) and self-reported measures (system usability score, overall task load index, presence score) will not differ in the PC keyboard and the PS3 gamepad conditions.*

2. Methodology

2.1. Experimental design

This study was a 2 × 2 × 2 repeated measures experiment; the *type of screen output*: PC screen and Head Mounted Display (HMD), the *number of views*: single view and multiple views, and the *type of robot control input*: PS3 gamepad and PC keyboard. The three factors were within subject factors, each one of the 30 participants experienced the eight interaction modes (combinations shown in Table 1) in random order to keep the unsystematic variation to a minimum (Field, 2013). The participants were asked to use the aforementioned eight different interaction modes to perform the following two tasks simultaneously: (a) robot path guidance (navigation) along vineyard rows while avoiding obstacles, and (b) targeting spray grape clusters. The grape clusters were in the same position for all participants.

2.2. Experimental setting and user task

The operator was situated remotely from the field while the robot was operated in the vineyard which was 150 m away. The operator had no direct eye contact with the robot in the field. Participants were asked to guide the robot along vineyard rows, avoiding obstacles, and to identify and spray grape clusters. They were asked to guide the robot, using the PS3 gamepad or the PC keyboard, for 50 m in a vineyard row, then make a turn 180° followed by navigating another 50 m in the next vineyard row. There were signs in the field to inform participants where to make a turn and when to stop. Each participant used all the eight user interfaces in random order. Video feedback from the robot's cameras and sensor information were displayed in the user interface. The operator could view the robot cameras either from a 17 inch PC screen or via a video eyewear (head mounted display) based on Vuzix Wrap 920AR, which also included a Wrap Tracker 6 TC; a motion tracker that plugs into a special port on the Wrap 920 enabled software to monitor the operator's direction and angle of view as well as movement. During the task, the participants' interaction with the system was monitored by the experimenter who took notes and video-recorded the entire experiment.

2.3. Participants

Thirty participants were involved in the study (7 females, 23 males), aged 28–65 (M = 39.8, SD = 9.3). Sixteen participants were farm workers, and 14 were agronomists, scientists with agricultural background. Educational levels were as follows: 27% had completed secondary school, 50% had completed university education, 10% had a postgraduate degree and 13% had a PhD degree.

2.4. Robot sprayer and user interfaces

The agricultural robot sprayer (Fig. 1) used in the experiment is based on the Summit XL mobile platform by Robotnik (http://www.robotnik.eu). The Summit XL is a medium-sized, high mobility all-terrain robot, with skid-steering kinematics based on four high power motor-wheels which was fitted for the spraying task (Adamides, 2016). The robot platform was adapted for teleoperation for both navigation and spraying tasks using a PS3 gamepad or a keyboard (keys used were W: forward, S: backward, A: turn left, D: turn right, and Spacebar for spraying on/off).

Eight alternative user interfaces configurations were developed reflecting the combination of all the aforementioned factors' levels examined in this study (Table 1).

2.5. Questionnaires

Study questionnaires were administered in the participants' native language (English or Greek). We provided this option in an attempt to minimize potential threats to the validity and reliability of questionnaire data obtained from non-native English speakers (Finstad, 2006). The Greek version of the System Usability Scale (Katsanos et al., 2012; Orfanou et al., 2015) was used. Likewise, the Greek version of General Self Efficacy scale was used (Glynou et al., 1994); the other questionnaires were translated by the authors and pilot-tested before the experiment.

2.5.1. Pre-experiment questionnaires

Immersive Tendency Questionnaire (ITQ). This questionnaire measures the differences in the tendencies of individuals to experience presence. The original version of the ITQ was developed by Witmer and Singer (1998), with a Cronbach's α of 0.78. The ITQ used in this experiment, was a revised version that consisted of 18 questions, as auditory and haptic items were not used during the experiment. The scoring takes into consideration four main groups: Focus – tendency to maintain focus on current activities, Involvement – tendency to become engaged in activities, Emotions – Tendency to become involved in activities, and Games – tendency to play video games.

General Self Efficacy scale (GSE). The GSE developed by Schwarzer and Jerusalem (1995) is used to assess respondents' general sense of perceived self-efficacy. GSE predicts how well one is coping with daily hassles as well as how well one adapts after experiencing stress. The responses to the GSE scale in each of the ten questions are provided on a 4-point scale and then summed up to yield the final composite score with a range between 10 and 40. According to Jerusalem et al. (1992), perceived self-efficacy reflects an optimistic self-belief that one can perform a novel or difficult task or cope with adversity. According to Schwarzer and Jerusalem (1995), based on samples from 23 nations, the Cronbach's α ranged from 0.76 to 0.90,

Table 1
The 2 × 2 × 2 experimental conditions and respective user interfaces for robot teleoperation.

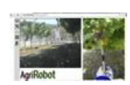
User interface	Factor 1: type of screen output(PC Screen vs HMD)	Factor 2: number of views(Single View vs Multiple Views)	Factor 3: type of robot control inputs(PC Keyboard vs PS3 gamepad)
User interface 1 PC screen + single view + PS3			
User interface 2 PC screen + multiple views + PS3			
User interface 3 PC screen + single view + keyboard			
User interface 4 PC screen + multiple views + keyboard			
User interface 5 HMD + single view + PS3			
User interface 6 HMD + multiple views + PS3			
User interface 7 HMD + single view + keyboard			
User interface 8 HMD + multiple views + keyboard			

Fig. 1. The agricultural robot sprayer.

with the majority in the high 0.80s.

Santa Barbara Sense of Direction scale (SBSOD). The SBSOD scale (Hegarty et al., 2002) was introduced in 2002 as a self-reported measure of environmental spatial ability. The recommended scoring procedure for the scale is to first reverse score for the positively phrased items, then sum the scores for all of the items together, and then divide the total by the number of items. The SBSOD score is a number between 1 and 7; the higher the score, the better the perceived sense of direction.

2.5.2. Post-task questionnaires

System Usability Scale (SUS). The SUS (Brooke, 1996) is a technology independent and reliable tool for measuring perceptions of usability. Bangor et al. (2008) analyzed a SUS dataset of 2300 individual surveys collected from more than 200 studies and found a Cronbach's α of 0.91. The SUS consists of a 10 item questionnaire with five response options for respondents; from 'strongly agree' to 'strongly disagree'. Five of the items are positively phrased, whereas the rest five are negatively phrased. The SUS scale score ranges from 0 to 100, where the higher the score, the better the perceived usability of the system.

Presence Questionnaire (PQ). The PQ measures the degree to which an individual experiences presence in a virtual environment and the influence of possible contributing factors on the intensity of this experience: Control Factors, Sensory Factors, Distraction Factors, and Realism Factors, delineated in Witmer and Singer (1998). Internal consistency measures of reliability for the PQ yielded a Cronbach's α of 0.88 (Witmer and Singer, 1998).

NASA Task Load Index (NASA-TLX) questionnaire. The NASA-TLX is an instrument that allows users to perform subjective workload assessments on operators' working with various human-machine systems which has been in use for more than 20 years (Hart, 2006; Hart and Staveland, 1988). NASA-TLX is a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration. The NASA-TLX has been in use for more than 20 years. It was translated into more than a dozen languages and is administered verbally, in writing or by computer. It has been subjected to a number of independent evaluations in which its reliability, sensitivity and utility were assessed and compared to other methods of measuring workload. In this study the NASA-TLX was administered on a computer (Vertanen and Adamides, 2012).

2.6. Experimental procedure

First, participants signed a consent form. Next, they answered a pre-experiment questionnaire that included demographics related questions, the ITQ scale, the GSE scale and the SBSOD scale. Next, the task (see Section 2.2) was explained to the participants and they were allowed to familiarize with the user interface for 5 min. Following the interaction with each UI, the participant was asked to answer the following: the SUS questionnaire (Brooke, 1996), the presence questionnaire (Witmer and Singer, 1998), and the NASA TLX (Hart and Staveland, 1988). In order to avoid fatigue effect, each participant used half of the UIs in one day and the remaining four UIs one week later. The experimental procedure was approved by the Open University of Cyprus' Ethical Committee.

2.7. Performance and self-reported measures

Usability of the different combinations was evaluated by measuring users' interaction effectiveness, interaction efficiency and overall satisfaction.

For the robot navigation task, effectiveness was operationalized by the total number of collisions: the fewer collisions, the more effective. Steinfeld et al. (2006) suggest using the number of obstacles avoided as one of the effectiveness metrics in the navigation task. However, we opted to use the number of actual collisions because in an agricultural field one might avoid obstacles along the path but still have collisions e.g. with tree stems or support poles on the side. For the spraying task, effectiveness was measured by the number of grape clusters sprayed, a binomial random variable with 24 trials (total number of targets). Similarly, efficiency was operationalized by time on task, which is the overall time required to complete the whole teleoperation task (navigation and spraying).

Subjective assessment of usability (i.e. perceived usability), was measured by the post-task 10-item System Usability Scale (SUS) (Brooke, 1996). Participants' self-reported feeling of presence (i.e. feeling that they are “there” while controlling the robot and detecting and spraying grape clusters) was measured using the Presence Questionnaire (PQ) (Witmer and Singer, 1998). The NASA-TLX was used to collect participants' subjective workload assessments (Hart, 2006; Hart and Staveland, 1988). These post-task questionnaires are delineated in the section “Questionnaires”.

We also measured other factors that may affect the user experience as covariates, specifically users' immersive tendency, efficacy, and sense of direction. These pre-experiment questionnaires are delineated in the section “Questionnaires”.

2.8. Statistical analyses

Statistical analyses of the collected data were conducted in order to compare the three factors. In all statistical analyses, the assumption of normality was investigated using the Shapiro-Wilk test. The d family of effect size was used to measure the magnitude of difference in standard deviation units. According to Leech et al. (2012), an effect size d of 0.5 means that the groups differ by one half of the pooled standard deviation and that usually d effect sizes vary from 0 to $\pm$ 1, but can also be more than 1, though it is relatively uncommon.

The linear mixed-effects models (LMM) enable one to fit linear mixed-effects models to data sampled from normal distributions. Recent texts, such as those by McCulloch and Searle (2000) and Verbeke and Molenberghs (2000), comprehensively review mixed-effects models. In a linear mixed-effects model, responses from a subject are thought to be the sum (linear) of so-called fixed and random effects. If an effect, such as experimental condition or type of event treatment, affects the population mean, it is fixed. If an effect is associated with a sampling procedure (e.g., subject, participant effect), it is random. In a mixed-effects model, random effects contribute only to the covariance structure of the data. The presence of random effects, however, often introduces correlations between cases as well. Though the fixed effect is the primary interest in most studies or experiments, it is necessary to adjust for the covariance structure of the data. The common statistical software such as SPSS, SAS, R etc., are based on maximum likelihood (ML) and restricted maximum likelihood (REML) methods for estimating the model parameters and for testing, versus the analysis of variance (ANOVA) methods in ANOVA and ANOVA with repeated measures. ANOVA methods produce an optimum estimator (minimum variance) for balanced designs, whereas ML and REML yield asymptotically efficient estimators for balanced and unbalanced designs. ML and REML thus present a clear advantage over ANOVA methods in modeling real data, since data are often unbalanced. The generalized linear mixed model (GLMM) extend the idea of LMM to non-normal data such as binary response in the same manner as generalized linear model extended the linear model to non-normal data (McCulloch and Searle, 2000).

The goal of this study is to examine the effect of the three interaction factors (type of screen output, number of views and type of robot control input device) on perceived usability (SUS score) and actual usability. Actual usability was measured in terms of efficiency (time in inverse scale) and effectiveness (number of grapes sprayed and number of collisions). A GLM (3-way ANOVA with repeated measures) was conducted on the three factors with measures on inverse time and the Linear mixed model (LMM) was used apart from effectiveness. The “*number of grapes sprayed*” is a binomial random variable with 24 trials therefore we used the logistic regression within the General Linear Mixed Model (GLMM) to model the probability to succeed in one try. Furthermore, in the case of “*number of collisions*”, we used the Poisson regression with log link function within the framework of GLMM. In all cases, the basic model included the three interaction factors (including their second and third order interactions) as fixed effects and the participants as a random effect to account for individual differences among them.

To examine the effects of the three interaction factors, in addition to the participants' sense of direction (SBSOD) on the AgriRobot system's actual usability – efficiency (time in inverse scale) and effectiveness (number of grapes sprayed and number of collisions) – and perceived usability (SUS score) we added the SBSOD score as a covariate to the fixed effect part of the basic model. To examine the effects of the three interaction factors in addition to the participants' immersion tendency (ITQ) on the AgriRobot system's actual usability – efficiency (time in inverse scale) and effectiveness (number of grapes sprayed and number of collisions) – we added the ITQ score as a covariate to the fixed effect part of the basic model. LMM was also used to examine the effects of the three interaction factors in addition to the participants' general sense of perceived self-efficacy on the perceived work load. In this analysis the fixed effects were the three interaction factors (including the second the third interactions) and the GSE score (as a covariate) and the participants were included as a random effect to account for individual differences and the dependent variable was the NASA-TLX total score.

Finally, to minimize potential fatigue effects the field experiment was conducted in two days, a week apart. We had 8 different user interface combinations (Table 1), based on the 3 factors ($2 \times 2 \times 2$). For each participant these 8 conditions were assigned randomly using a web based random number generator. So each participant was asked to come to the experimental station on two different days and carry out 4 combinations each time. Therefore, no bias due to learning effects was expected in the results but we also statistically investigated it using GLMM with the 3 factors and the "*day*" as a fourth factor without interactions.

3. Results and discussion

3.1. Results

3.1.1. Pre-experiment results

The mean score of the 30 participants for the ITQ scale was 71.77 (SD = 12.06, minimum and maximum scores at 51 and 96, respectively) with high reliability (Cronbach's $\alpha = 0.776$). Participants' perceived self-efficacy score (M = 30.57, SD = 3.54) reflects an optimistic self-belief (Schwarzer, 1999), such as that the participants could cope with adversity, e.g. teleoperating a robot sprayer. The reliability of the GSE was high; Cronbach's $\alpha = 0.836$. Participants' mean score on the Santa Barbara Sense of Direction scale was M = 4.95 (SD = 0.93 with high reliability, Cronbach's $\alpha = 0.809$), which is above the scale's reported mean of 4.7 (Hegarty et al., 2002).

3.1.1.1. Effects of participants' immersion tendency on presence. The Linear Mixed Model analysis results indicated that the type of ***robot control input device F(1,228) = 35.184, p < 0.001,*** as well as the ***number of views F(1,228) = 7.870, p < 0.005,* are both significant factors** influencing the perceived sense of presence. The ***type of screen output* was not a significant factor** for the presence dependent when participants' immersion tendency was used as a covariate. Likewise, the covariate (ITQ score) **was not statistically significant *F(1,230) = 0.003, p = 0.957*.** The interactions between the three factors were also not significant.

Regarding the type of *robot control input devices* when participants were guiding the robot using the PC keyboard, their perceived sense of presence was significantly higher (M = 92.58, SD = 17.86), compared to those who were using the PS3 gamepad (M = 80.88, SD = 21.09), with an effect size *d=0.598*. The participants' perceived sense of presence was also significantly higher when they had the multiple views user interface (M = 89.49, SD = 19.27), compared to when they had feedback from the single view camera (M = 83.96, SD = 21.12), with an effect size *d= 0.273*.

3.1.1.2. Effects of participants' sense of direction on actual and perceived usability. GLMM were conducted on observed and perceived usability for the three factors (type of screen output, number of views and type of robot control input device). The interactions between the three factors were not significant.

Regarding the participants' sense of direction, in relation to the three factors, it was found that **the SBSOD score was not statistically significant.** Specifically in terms of efficiency (time on task) the SBSOD was ***F(1,231) = 1.802, p = 0.181***; regarding effectiveness, in relation to targets sprayed ***F(1,231) = 0.298, p = 0.586*** and number of collisions ***F(1,231) = 0.223, p = 0.637***). Finally in relation to perceived usability (SUS score) the SBSOD was again not significant ***F(1,231) = 0.418, p = 0.518***.

3.1.1.3. Learning effects. To evaluate for potential practice/learning effects we ran again the GLMM with the 3 factors (type of screen output, number of views and type of robot control input device) and added the "*day*" as fourth factor without interactions. In all examined outcomes **we did not find any significant "day" effect**. Specifically, in terms of **effectiveness**: Collisions: F(1,231) = 0.537, p = 0.464 and grapes-sprayed: F(1,231) = 0.198, p = 0.657. With regards to **efficiency**: Time: F(1,231) = 0.008, p = 0.931. Similarly, the "day" factor did not have any statistical significance on the **subjective-workload**: F(1,231) = 1.785, p = 0.183, neither on **subjective usability** (SUS): F(1,231) = 3.116, p = 0.079.

3.1.2. Post-experiment results

Table 2 summarizes the descriptive statistics of the dependent variables per factor (type of screen output, number of views and type of robot control input device).

3.1.2.1. Effects of the three factors on actual and perceived usability. GLMM were conducted on observed and perceived usability for the three factors (type of screen output, number of views and type of robot control input device). The interactions between the three factors were not significant.

In terms of **HRI effectiveness** both in spraying and in robot path guidance, **the only significant factor was the *number of views F(1, 232) = 294.856, p < 0.001* and *F(1,232) = 34.633, p < 0.001***, respectively. Specifically for the spraying task, participants that had multiple views sprayed significantly more grape clusters (M = 14.03 SD = 7.39), than those that had only a single view (M = 4.19, SD = 3.95), with an effect size $d = 1.66$. For the robot path navigation task, participants with multiple views had significantly fewer collisions (M = 0.51 SD = 0.81), compared to those with only a single view available (M = 1.28, SD = 1.44), with an effect size $d = -0.65$.

In terms of **HRI efficiency,** a GLM (3-way ANOVA with repeated measures) was conducted on the three factors with measures on inverse time. The interactions between the three factors were not significant. The **number of views** and the **robot control inputs were both significant factors *F(1,29) = 4.732, p < 0.05, $\eta^2 = 0.140$* and *F(1,29) = 13.454, p < 0.001, $\eta^2 = 0.317$***, respectively. For the whole task (robot path guidance, identification of targets, and spraying), participants interacting with the robot using the PC keyboard and with the multiple views available (M = 222.50, SD = 116.21) required significantly less time to complete the task, compared to those in the PS3 gamepad and the multiple views condition (M = 259.10, SD = 109.37).

Finally, in terms of **perceived usability, the only significant factor** was the **robot control input device; *F(1,232) = 48.232, p < 0.001*.** The PC Keyboard was at the 70th percentile (M = 70.75, SD = 16.30) which is above average (Bangor et al., 2008), while the PS3 gamepad controller at the 57th percentile (M = 57.79, SD = 16.44), which is below average, with an effect size $d = 0.79$. The interactions between the three factors were also not significant.

3.1.2.2. Effect of the three factors on the subjective perceived workload. To investigate whether the different interaction styles influenced the perceived workload (NASA TLX index), the LMM with repeated-measures on the three factors was performed, where the three factors were within-subject-factors, with measures on NASA-TLX. The interactions between the three factors were not significant.

There was a significant main effect of screen type on perceived workload index; *F*(1,29)=4.92 *p < 0.05, $\eta^2 = 0.145$*. The PC screen contributed significantly less to the workload index compared to the HMD. There was also **a significant main effect of the *type of robot control input device; F*(1,29)=28.13, *p < 0.001, $\eta^2 = 0.492$*.** Specifically, participants using the PS3 gamepad reported a significantly higher perceived workload index score, compared to those using the PC keyboard. There was also **a significant main effect in the interaction between *type of robot control device* and *number of views* on the perceived work load index; *F*(1,29)=4.07, *p < 0.05, $\eta^2 = 0.144$*.**

Specifically, it was found that the perceived workload index does not depend on the value of the *number of views* but rather on the *type of robot control tool*. The PS3 controller increased the perceived workload index in both the single and multiple view conditions (M = 51.05 and M = 50.87, respectively), while the PC keyboard had lower perceived workload index score, again for both the single and multiple views conditions (M = 41.25 and M = 35.86, respectively). A LMM with repeated-measures on the three factors and the GSE score of the participants' as a covariate indicated that the **GSE score was not a significant factor; $F(1,231) = 1.37$, $p = 0.24$; the only significant factors were the screen type and robot control input device $F(1,231) = 6.34$, $p < 0.01$ and $F(1,231) = 53.71$, $p < 0.001$, respectively.**

3.2. Summary of findings

- Participants were significantly more effective (i.e., had less collisions and sprayed more grape clusters), both in spraying and in robot path guidance, when they had multiple views, than when they had a single view; 60.16% and 234.84%, respectively.
- With a single view, participants required significantly less time to complete the task, than when they had multiple views (12.08% difference).
- Using the PC keyboard required significantly less time to complete the task by 11.32%, compared to those using the PS3 gamepad.
- The PC keyboard had significantly higher perceived usability (SUS score) compared to the PS3 gamepad controller by 13 percentiles.
- Participants using the PC keyboard, reported a significantly lower perceived workload index, compared to those using the PS3 gamepad controller by 24.30%.
- With multiple views and the PC keyboard condition, participants' perceived sense of presence was significantly higher, than when they had a single view and operated with the PS3 gamepad.
- The PC screen contributed significantly less to the workload index, compared to the head mounted display by 9.09%.

3.3. Discussion

Two tasks were simultaneously performed with the AgriRobot teleoperated sprayer system: path guidance (robot navigation) and detecting and spraying the targets in field conditions. The field study findings related to three user interface factors of the AgriRobot system; the number of views (single view and multiple views); the type of screen-output (PC screen and HMD), and the type of robot control inputs (PS3 gamepad and PC keyboard). The findings partially supported the three research hypotheses: different dependent variables were significantly affected by each factor. These findings are discussed in the following.

Type of screen output: ***This factor influenced only the perceived workload index***. Specifically, it was found that the PC screen contributed significantly less to the workload index, compared to the HMD. Lichtenstern et al. (2013) also report several user inconveniences with HMD and higher overall task load index. However, they also found that this frustration decreases over the course of time, but this could not be investigated in the context of this study. The type of screen output was not found to be significant for the presence covariate to the participants' immersion tendency.

Number of views: Our results confirm findings from Yanco and Drury (2007) who concluded that, "when teleoperating a robot, operators rely on the video to determine the best way to navigate the environment". In addition, Drury et al. (2007), concluded that "a video centric interface is more effective in providing good surroundings and activities awareness". Murakami et al. (2008) used an omnidirectional camera and a field map for the operator to observe the teleoperated vehicle during teleoperation. ***The placement of a camera on the top-back of the robot enhanced the surroundings awareness, while the placement of a camera on the end-effector sprayer, improved target identification, thus improving activity awareness***. Fig. 2 illustrates the importance of the multiple views user interface, compared to a single view user interface. Operators driving the robot with a single camera could not identify obstacles (bucket) in front of the robot wheels, nor could they easily identify grape clusters to spray. By contrast, operators with the multiple views user interface could identify both the obstacle and grape clusters to spray, much more effectively.

Type of robot control inputs: ***The PC keyboard was found to be significantly superior to PS3 gamepad controller in terms of time to complete the task, perceived usability, perceived workload index and perceived sense of presence***. This corresponds to results of other studies (Randelli et al., 2011; Velasco et al., 2015). However, all participants were far more experienced in using a keyboard than in using a PS3 gamepad controller. Similarly, in a previous study investigating the usability of input devices for spraying grape clusters (Adamides et al., 2013), it was found that a typical pointing device (mouse) outperformed a more innovative one (Wiimote) in terms of both perceived and actual usability. More experiments are needed to re-evaluate the effect of robot control input type and investigate how behavior changes along time, i.e. after using the robot control inputs for some time in which the user gains experience.

Teleoperation for agricultural robotics: Highest task success for spraying grape clusters (across conditions) was 58%, in similar range to low performance of harvesting robots i.e., average 66%, (Bac et al., 2014). In the current experiments, detection was conducted solely by the human operator without support from automatic detection algorithms. Furthermore, there was an added complexity of detecting the clusters while advancing along the row. Autonomous detection rates average about 85% (Kapach et al., 2012) and these can be improved by incorporating more

Table 2
Dependent variables collected per examined UI factors.

Factors	Conditions	N	Grapes sprayed (0–24)		Collisions (0–7)		Completion time (s)		SUS score (0–100)		Overall task load index (0–100)		Presence questionnaire score (37–132)	
			M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Type of screen output	PC screen	120	9.13	7.65	0.90	1.27	224.17	118.40	65.95	16.16	42.63	17.57	88.06	19.26
	HMD	120	9.09	7.77	0.88	1.18	225.41	105.18	62.58	18.81	46.89	18.31	85.39	21.41
Number of views	Single view	120	4.19	3.95	1.28	1.44	210.34	89.09	64.14	17.08	46.14	19.33	83.96	21.12
	Multiple views	120	14.03	7.39	0.51	0.81	239.24	129.32	64.39	18.14	43.38	16.60	89.49	19.27
Robot control inputs	PS3 gamepad	120	8.66	8.12	0.85	1.30	238.27	113.03	57.79	16.44	50.95	17.83	80.88	21.09
	PC keyboard	120	9.56	7.25	0.93	1.15	211.30	109.27	70.75	16.30	38.57	16.06	92.58	17.86

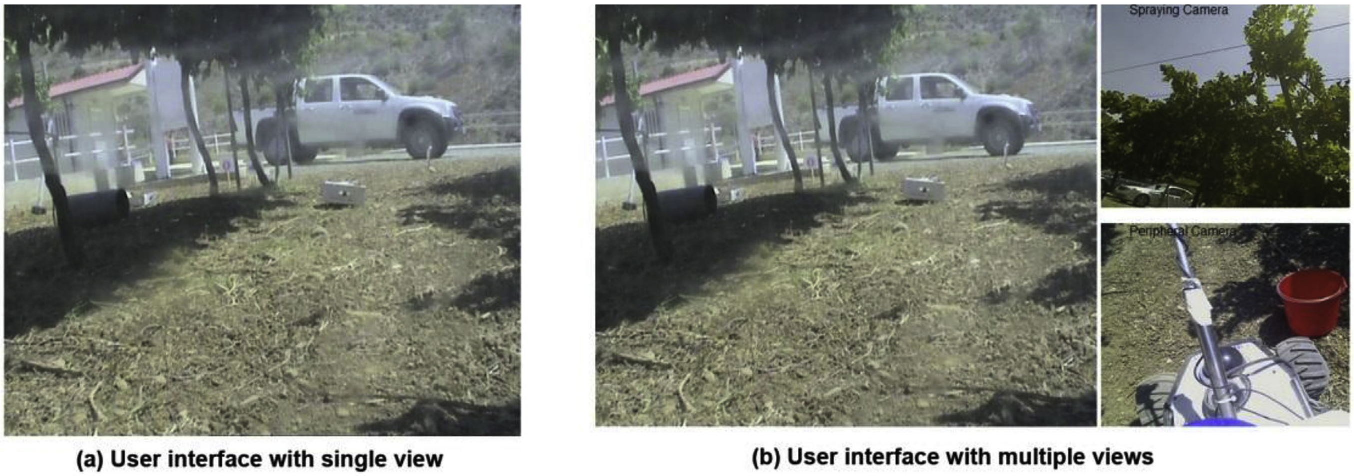


Fig. 2. Multiple vs single view factor.
Left: single view from main camera, Right: multiple views from main, peripheral and end-effector target cameras.

advanced detection algorithms and combining a human in the loop (Bechar and Edan, 2003). Blackmore et al. (2005) argues that the 95% is the lowest barrier for the detection rate in order for the spraying process to be economically feasible. Correa et al. (2012) reported a 95% hit rate for red grape clusters but with artificial white background. Berenstein (2016) yielded 91% for autonomous target detection and 94% detection in human-robot collaboration. The AgriRobot system can include automatic algorithms and human-robot collaboration to improve performance. Autonomous navigation and spraying have been successfully implemented (Berenstein, 2016; Guzman et al., 2016) and therefore there is less need to involve the human operator in this task. Multiple (and simultaneous) tasks during robot teleoperation influence performance (Doisy et al., 2016; Eliav et al., 2011; Fong et al., 2001). Hence, we recommend to have the human-robot collaboration focus only on the target detection task since it is the most complicated one. This is expected to further improve the performance.

4. Conclusions and recommendations

Semi-autonomous teleoperation of an agricultural robotic system requires the design of an interface for effective and efficient human-robot collaboration. This article presented findings related to the human factors and ergonomics for agricultural robot teleoperation. The findings were demonstrated through a vineyard sprayer robot constructed on top of an operational robotic platform. The robot was teleoperated in the field using different interaction modes which included the type of screen output (PC screen vs head mounted display), the number of views (single vs multiple), and the type of robot control input device (PS3 gamepad vs PC keyboard). The user was responsible for navigation, target detection and spraying of grape clusters.

Results indicated that participants were significantly more efficient and more effective with *multiple views*; specifically with the feedback from the main camera, the peripheral camera, and from the end-effector camera. The *type of screen output influenced only* the perceived workload index. Specifically, the PC screen contributed significantly less to the workload index, compared to the HMD. Participants using the PC keyboard to *control the robot* had significantly higher efficiency, and reported higher perceived usability, lower perceived workload index and higher perceived sense of presence compared to using the PS3 gamepad.

Another aspect of the user interface that might have improved HRI awareness is the placement of sonar sensor indicators on the user interface. To improve system awareness, an indicator to provide feedback about the robot's battery level was also included on the user interface. Study participants argued that an indicator that was missing from the user interface, and was noted for future design and implementation, was the spray tank level. Given the specific task of spraying, it was suggested that in order to enhance system and activity awareness, the operator must know how much liquid was in the robot's tank available to spray. The same suggestion was made by four usability experts who were involved in heuristic evaluations (Adamides et al., 2016) using a set of research-based heuristics for the design of robot teleoperation (Adamides et al., 2015).

Based on these results, specific recommendations for mobile field robot teleoperation to improve HRI awareness for the agricultural spraying task include: placing a camera on top of the end-effector sprayer provides for fast and accurate target identification and spraying verification, thus improving activity awareness; placing a camera at the back-top of the robot provides peripheral vision and enables the operator to locate obstacles around the robot wheels, thus improving location and surroundings awareness; the PC screen is preferred as an output device, which might be attributed to the fact that humans are more familiar with PC screens or monitors in general to view at a remote location; the PC keyboard is the preferable control input.

Future work should include longitudinal studies to investigate how behavior changes along time, i.e. after using the robot control inputs for some time in which the user gains experience. Advanced detection algorithms should be developed and included to the AgriRobot system, along with new sensor technologies, to overcome the low human success rate for detecting grape clusters, and to overcome the changing illumination conditions in the field. Focus on the target detection task only may also ensure improved performance.

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