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Vision and Radar Steering Reduces Agricultural Sprayer Operator Stress without Compromising Steering Performance

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HIGHLIGHTS

- Stress was measured in professional sprayer operators who, while working, drove manually and with vision or radar steering.
- Vision and radar steering reduced the average operator stress rate by 48% relative to manual steering.
- The use of automatic guidance could have a dramatic positive effect on the health of sprayer operators.
- Sprayer steering performance was reported for professional operators and both vision and radar guidance for the first time.

ABSTRACT. *Self-propelled agricultural sprayer operators work an average of 15 h d^{-1} in peak season, and steering is the task that causes the operator the most stress because of the large number of stimuli involved. Automatic guidance systems help reduce stress and fatigue for operators by allowing them to focus on tasks other than steering. Physiological signals like skin conductance (electrodermal activity, EDA) change with stress and can be used to identify stressful events. The objective of this study was to determine if using a commercially available vision and radar guidance system (VSN®, Raven Industries) reduces agricultural sprayer operators' stress compared to when they are steering manually. Four male professional sprayer operators participated in this study. Each operator performed his job duties normally in GPS-guidance-planted fields, at his self-selected speed, except to drive some passes manually and others with VSN in the same field. EDA was measured with an Empatica E4 wristband, and stressful events were quantified. Machine data (e.g., speed, RTK-GPS, and VSN metrics) were collected from each sprayer via CAN logs. The steering type, stress rate (e.g., stressful events min^{-1}), and steering performance (cross-track error standard deviation, XTE SD) were determined for each pass. In total, 51 passes (23 manual, 28 VSN) in six fields were analyzed. Operators using VSN had a significant reduction (48% lower, $p < 0.001$) in their stress rate compared to when they were steering*

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manually. There was no significant difference in the XTE SD for the steering type. The use of an automatic guidance system such as VSN could have a dramatic positive effect on the health of sprayer operators, especially during the long workdays of the peak spraying season, and could reduce the negative effects that stress and fatigue have on steering performance, mistakes, and accidents.

Keywords. *Electrodermal activity, Guidance systems, Machine vision, Precision agriculture, Radar, Skin conductance, Vehicle guidance.*

Operators of self-propelled agricultural sprayers work an average of 15 h d^{-1} in peak season (Dey and Mann, 2010), and steering is the task that causes the operators the most stress because of the large number of stimuli involved (Kocher et al., 2000; Sinden et al., 1985). Automatic guidance systems help reduce operator stress (Kocher et al., 2000; Kviz and Kroulík, 2017) and fatigue (Amiama Ares et al., 2011; Berglund and Buick, 2005; Billingsley and Schoenfisch, 1997; Kocher et al., 2000) by allowing operators to focus on tasks other than steering (Amiama Ares et al., 2011; Berglund and Buick, 2005; Billingsley and Schoenfisch, 1997; Kocher et al., 2000). Stress and fatigue negatively affect operators' situational awareness and performance and thus increase their likelihood of mistakes and accidents (Houshyar and Houshyar, 2018; Irwin et al., 2019; Karimi and Faghri, 2021).

Satellite guidance is a common form of agricultural guidance, but it has two drawbacks that limit its value for operating agricultural sprayers in emerged row crops. First, the precision satellite guidance required to navigate row crops is an expensive fixed cost (English et al., 2014), so farmers with smaller operations may not find the technology cost-effective. Second, custom applicators contracted to spray a field often do not have access to the satellite guidance lines that were used to plant the field.

Vision-based guidance systems were developed in the 1980s (Reid and Searcy, 1987; Reid et al., 2000), and various methods have been used to improve their performance (Guerrero et al., 2013). VSN® (Raven Industries, Sioux Falls, S.D.) is a commercially available vision-based guidance system that uses a stereo camera to navigate a vehicle through emerged row crops (fig. 1). It is engaged like GPS guidance, and the guidance system steers the vehicle instead of requiring the operator to steer the vehicle. VSN also has a mode in which the vehicle can use radar (VSN Full Canopy) instead of the stereo camera to detect crop rows when the crop canopy is too dense for the camera to see the ground (fig. 2).

Stress is a biological reaction that changes a person's emotional state from calm to excited (Healey and Picard, 2005). Physiological signals such as skin conductance (electrodermal activity, EDA) change with stress level (Borghini et al., 2020; Giorgi et al., 2021; Healey and Picard, 2005; Sharma and Gedeon, 2012), including mental stress (Giorgi et al., 2021; Schuurmans et al., 2020) and stress from driving (Healey and Picard, 2005), which are similar to the stresses that sprayer operators experience in performing their work. EDA has two components: a low-frequency tonic response, called skin conductance level (SCL), and a high-frequency phasic response, called skin conductance response (SCR) (Braithwaite et al., 2013). SCR is typically of interest because it is a result of a specific stimulus (Caruelle et al., 2019), and it can be measured with validated wristband sensors such as the Empatica E4 (Giorgi et al., 2021).

Figure 1. Photo of a VSN (black box) positioned in front of the right front wheel on a rear boom sprayer. The stereo camera lenses are behind the clear windows of the VSN enclosure.

Figure 2. Photo of a high-clearance front boom sprayer operating in a canopied corn field. Under these conditions, VSN Full Canopy uses radar sensors instead of a stereo camera to detect crop rows.

Because operating a sprayer is stressful and automatic guidance systems help reduce stress and fatigue, our hypothesis was that an automatic guidance system (VSN) would reduce agricultural sprayer operators' stress compared to steering manually.

Materials and Methods

Participants and Protocol

Five male professional self-propelled sprayer operators were enrolled in this study. The research protocol was approved by the South Dakota State University Institutional Review Board, and each subject consented to his involvement before participating. All subjects had experience with GPS guidance (VSN is engaged in the same way) and used VSN for at least a few days to acclimate to it before participating in the study. Each subject was instructed to perform his job duties (while working) normally in GPS-guidance-planted fields, at his self-selected speed, except to drive some passes manually and others with VSN in the same field and between tank fills. Each subject was instructed to wear an Empatica E4 wristband (Empatica Inc., Boston, Mass.) on his non-dominant hand, and each participated without an investigator present. One subject was not included in the study because he did not drive in the same field both manually and with VSN while wearing a wristband. The four participating subjects and their sprayers are listed in table 1.

Data Collection

Machine CAN logs, which include speed, RTK-GPS, and VSN metrics, were acquired from each participant's sprayer (RS1™, Raven Industries, Sioux Falls, S.D.). System measurements were parsed from CAN logs at 5 Hz, except those from Subject 2, which were at 2 Hz. Skin conductance (EDA) data from the wristband were collected at 4 Hz. Data were imported and processed in MATLAB R2020b (MathWorks, Natick, Mass.).

Machine Measurements

A local *x-y* coordinate system was calculated from GPS latitude and longitude. The haversine equation is more accurate than a cosine-based equation for very short global distances (Daidzic, 2017; Sinnott, 1984); thus, for each field, great circle distances were calculated (Daidzic, 2017; Tsai, 2011) to map each GPS measurement in the local coordinate system:

$$d = 2R\sin^{-1}\sqrt{\sin^2\left(\frac{lat_2 - lat_1}{2}\right) + \cos\left(lat_1\right)\cos\left(lat_2\right)\sin^2\left(\frac{lon_2 - lon_1}{2}\right)} \quad (1)$$

where

d = calculated distance

R = Earth's radius (6371 km; Daidzic, 2017)

Table 1. Subjects and sprayer information.

Subject	Spraying Experience (years)	Sprayer Model and Boom Length	Region	Crop and VSN System	Spraying Dates (2021)
S1	12	Miller Nitro 7310, 30.5 m (100 ft) front boom	West central Illinois	Soybeans (VSN vision)	July 8 and 23
S2	7	Case IH Patriot 4440, 36.6 m (120 ft) rear boom	Central Indiana	Soybeans (VSN vision)	July 27
S3	2	New Holland Guardian SP370, 36.6 m (120 ft) front boom	Northwest Iowa	Tasseled corn (VSN radar)	July 29[a]
S4	6	Miller Nitro 7370, 36.6 m (120 ft) front boom	North central Iowa	Tasseled corn (VSN radar)	July 21[b]

[a] Subject S3 drove in his own crops; the other subjects were contracted to drive in customers' crops.

[b] Subject S4 drove in two fields on this day.

lat = latitude (radians)

lon = longitude (radians).

Only straight row passes were evaluated (not headlands), and the start and end of passes were identified based on speed transitions (18 km h^{-1} for Subjects 1, 2, and 4; 5 km h^{-1} for Subject 3). Start and end points were occasionally adjusted to remove segments of turning into or out of the headlands and when one steering type was used for a short segment and the other type was used for the rest of the pass. Row passes at the edge of the field were excluded, except in one case in which Subject 1 used each steering type about half the distance on the same pass and physically stopped in between. Only segments longer than 150 m were used. In locations where it was clear that the operator steered the sprayer around a hazard, the end of the evaluated row was positioned before the steering deviation. For each of the 51 passes, the steering type was recorded from the RS1, and the average speed, duration, and distance of the pass were calculated.

For each pass, a linear regression was fit to data in the local coordinate system to estimate a guidance line (Amiama Ares et al., 2011; Han et al., 2004; Min et al., 2008; Rounsaville et al., 2016; Spekken et al., 2014; Wu et al., 2006). A least-squares regression can have large fitting errors when its slope is nearly vertical (Wu et al., 2006), so when the absolute value of the *x-y* slope between the first and last points was greater than 1, the axes were transposed for the analysis. For each data point, the orthogonal cross-track error (XTE) was calculated (Han et al., 2004; Rounsaville et al., 2016). Steering performance was quantified as the XTE standard deviation (XTE SD) of the pass (Gomez-Gil et al., 2011). The first derivative of XTE was calculated with a Savitzky-Golay filter (Savitzky and Golay, 1964) in a 1 s window before and after each point (i.e., an 11-point filter for 5 Hz data and a 5-point filter for 2 Hz data). A steering adjustment was defined as a first derivative zero-crossing. The number and rate of steering adjustments were calculated for each pass.

EDA Measurements and Stressful Events

The EDA data were filtered twice with a Hampel filter (MATLAB hampel function with a window of 1 s on each side) to remove artifacts (Jebelli et al., 2019), e.g., motion and loose connection artifacts (Caruelle et al., 2019). The filtered data were evaluated with EDA QA (Kleckner et al., 2017) and found to pass the quality check in the analysis regions. An infinite impulse response filter (IIR, MATLAB filtfilt function) (Kleckner et al., 2017) was then applied with a window of 1 s to smooth the data. Peaks and valleys of the smoothed data were identified (MATLAB findpeaks function) (Bitkina et al., 2019). The magnitude, duration, and area under the curve (Healey and Picard, 2005) of stressful events, i.e., those with a minimum threshold of 0.01 μS (Caruelle et al., 2019; Lajante et al., 2012) and a duration of 1 to 3 s (Dawson et al., 2011; Lajante et al., 2012), were calculated, and the time of the event was recorded. Wristband and CAN time were aligned via UTC time. The number and rate of stressful events were calculated for each pass.

Using the same method, stressful events were also calculated from three EDA datasets (drive04, drive10, and drive15) from the automobile Drivedb database (Goldberger et al., 2000). In that study, three subjects drove a prescribed course in Boston, Massachusetts (Healey and Picard, 2005). For those three subjects (D04, D10, and D15), the number and rate of stressful events were calculated for each segment of city driving, highway driving, and rest based on the segmented regions described for the drive04 (Liu and Du, 2018), drive10 (Healey and Picard, 2005), and drive15 (Ollander et al., 2016) datasets, respectively. See Burgers (2022a) for details.

Summary Metrics and Statistics

Mean stress rate (e.g., stressful events min^{-1}) and steering adjustment rate were calculated as the total number of events divided by the total time for each steering type for each subject (i.e., they were not averaged per pass because passes were not all the same duration). Stress rate mean of means were calculated as the mean of the subject means to give equal weight to each subject (i.e., to not give equal weight to each pass or driving segment). For the sprayer operators, the subject-normalized stress rate was calculated for each pass as the stress rate of the pass divided by the subject's manual mean stress rate. For the automobile drivers, the subject-normalized stress rate was calculated for each segment as the stress rate of the segment divided by the subject's city driving mean stress rate. Means for XTE SD were averaged per pass, and stressful event magnitude, duration, and area under the curve were averaged on a per event basis.

Two-way analysis of variance (ANOVA) was performed on the response variables with steering type and subject as categorical variables (Minitab 20, Minitab, State College, Pa.), and $p < 0.05$ was considered significant. Data transformations were applied when data were not normally distributed (Box-Cox $\lambda = -0.5$ for the magnitude per event, area under the curve per event, and XTE SD; $\lambda = 0$ (ln) for duration per event; and $\lambda = 2$ for steering adjustment rate).

Results

Sprayer Operator Stress

The locations of the stressful events were mapped in their local coordinate system. For example, in figure 3, Subject 3 started at the bottom right (relative to the figure), sprayed clockwise around the field boundary, and then made horizontal passes working his way from the bottom to the top. In his first five passes, he used VSN and averaged 1.2 stressful events min^{-1}. In his first manual pass (y = 220 m), he had a relatively low stress rate (1.8 stressful events min^{-1}), but in the second pass (y = 260 m) his stress rate increased (6.8 stressful events min^{-1}) and he physically stopped in the middle of the field (x = 450 m); he then finished the pass with VSN at about a third of the stress rate (2.4 stressful events min^{-1}). He had committed to steering manually, so he did the next two passes manually and

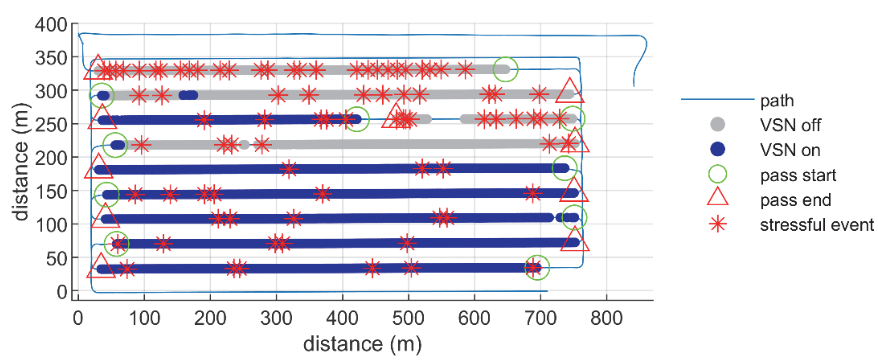

Figure 3. Map of passes, steering type, and stressful events for Subject 3.

had an increasing stress rate (2.8 and 8.1 stressful events min^{-1}). Finally, he exited the field to the road (y = 385 m).

In total, 51 passes (23 manual, 28 VSN) in six fields were analyzed. There was a significantly lower stress rate when steering with VSN than manually (an average of 2.8 vs. 5.4 stressful events min^{-1}, $p < 0.001$, fig. 4a and 4b, table 2). Subject-normalized stress rates are shown in figures 4c and 4d; the normalized stress rate was less than 1 (the subject's

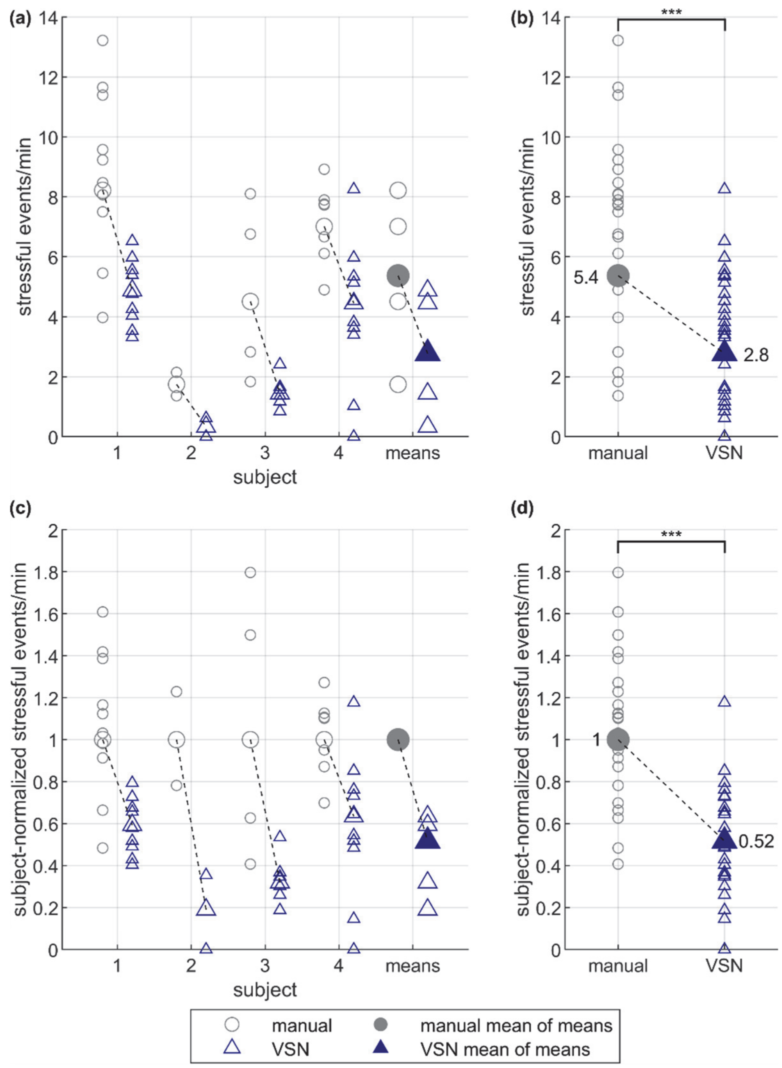

Figure 4. Individual value plots of (a) stress rate per subject, (b) stress rate aggregated from all subjects, (c) stress rate normalized to each subject's manual mean per subject, and (d) stress rate normalized to each subject's manual mean aggregated from all subjects for each steering type. Each small shape represents the measurement of one pass, each medium shape represents the steering type mean for each subject, and each large filled shape represents the mean of means for each steering type. The average operator had a 48% lower stress rate when steering with VSN compared to manual steering (range of 37% to 81% lower). Significance is indicated between steering types (* = p < 0.001).**

Table 2. Pass and stress rate results by steering type and subject. Normalized stressful events min^{-1} are normalized to the subject's manual total stressful events min^{-1}. Pass metrics are reported as mean ±SD. Significance is indicated between steering types (* = p < 0.001).**

Subject	Steering Type	Total Passes	Total Time (s)	Pass Duration (s)	Pass Speed (km h^{-1})	Total Stressful Events (min^{-1})	Normalized Stressful Events (min^{-1})
S1	Manual	10	584	58 ±23	24.5 ±1.7	8.2	1
	VSN	9	665	74 ±23	25.4 ±1.4	4.9	0.59
S2	Manual	2	172	86 ±2	26.2 ±0.7	1.7	1
	VSN	2	181	90 ±7	24.5 ±0.6	0.3	0.19
S3	Manual	4	719	180 ±54	10.3 ±0.8	4.5	1
	VSN	6	1209	202 ±35	10.5 ±0.4	1.4	0.32
S4	Manual	7	590	84 ±15	22.3 ±0.2	7.0	1
	VSN	11	809	74 ±20	22.5 ±0.1	4.4	0.63
Mean of means	Manual	NA	516	NA	NA	5.4	1
	VSN	NA	716	NA	NA	2.8***	0.52***

manual mean) for all but one of the 28 VSN passes. The four subjects on average had a 48% lower stress rate when steering with VSN compared to steering manually (range of 37% to 81% lower, fig. 4c and 4d, table 2). There was also a significant difference in the stress rate between participants (p < 0.001).

There was no significant difference in the stressful event magnitude or stressful event area under the curve between steering types, but there was a significant difference between subjects (p < 0.001 for each, table 3). The duration of the stressful events was significantly longer with VSN compared to steering manually (2.0 ±0.3 s vs. 1.7 ±0.2 s, p = 0.002), but there was no significant difference between subjects.

Automobile Driver Stress (Drivedb Database)

As a comparison, the automobile drivers' stress rate and the subject-normalized stress rate are shown in figures 5a and 5b. City driving, highway driving, and rest segments had on average 4.2, 3.0, and 1.1 stressful events min^{-1}, respectively. Relative to city driving, the three subjects had on average a 24% lower stress rate for highway driving and a 74% lower stress rate for rest.

Steering Performance

There was no significant difference in steering performance (XTE SD) between steering types (p = 0.7) or subjects (p = 0.058), as shown in figure 6 and table 4. Histograms of all the XTE measurements from each subject are shown in figure 7. See Burgers (2022b) for local coordinate system and XTE data for each pass and the processed histograms. There was no significant difference in the steering adjustment rate between steering types, but there was a significant difference between subjects (p < 0.001, table 4).

Table 3. Stressful event magnitude and stressful event area under the curve per event by subject. Values are reported as mean ±SD.

Subject	Magnitude per Event (μS)	Area under Curve per Event (μS-s)
S1	0.11 ±0.07	0.12 ±0.07
S2	0.013 ±0.002	0.010 ±0.001
S3	0.030 ±0.018	0.028 ±0.017
S4	0.087 ±0.062	0.086 ±0.063

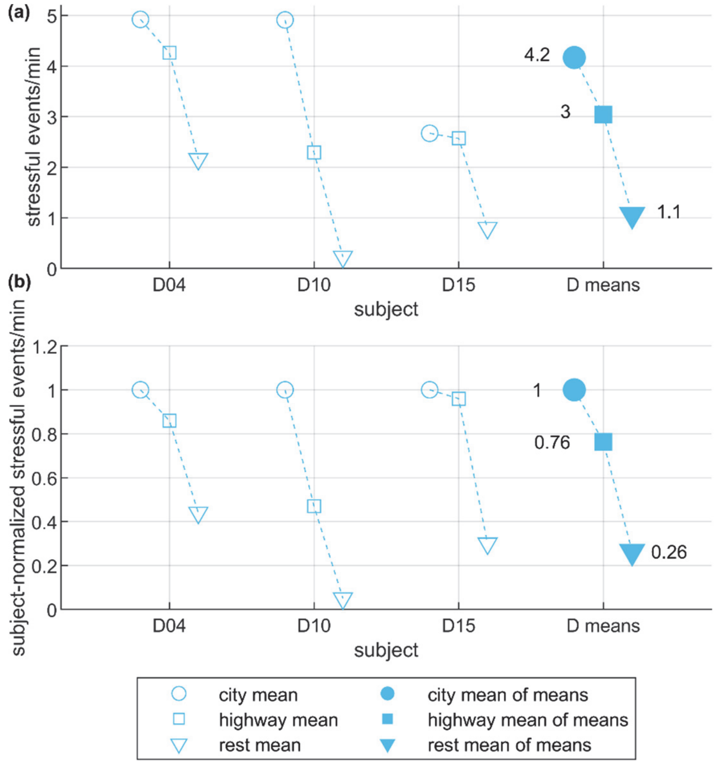

Figure 5. Automobile driving (a) stress rate and (b) stress rate normalized to each subject's city driving for drive04 (D04), drive10 (D10), and drive15 (D15) subjects in the Drivedb database. Each open shape represents the mean for a driving segment, and the filled shape represents the mean of means for a driving segment. On average, the stress rate was 24% lower for highway driving compared to city driving.

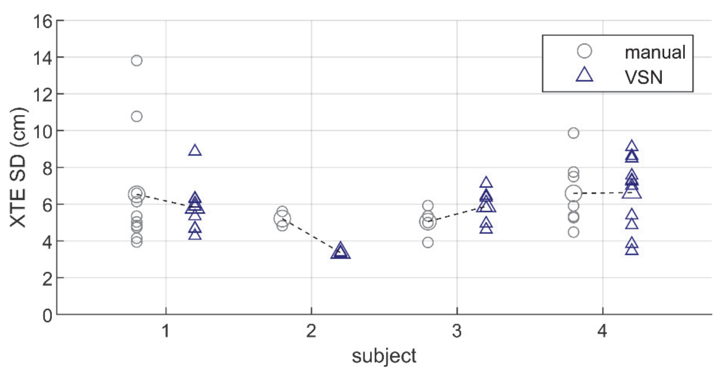

Figure 6. Individual value plot of cross-track error standard deviation (XTE SD) for each steering type and subject. Each smaller shape represents the measurement of one pass, and the larger shape represents the steering type mean for each subject.

Table 4. Steering performance by steering type and subject. Values are reported as means ±SD.

Subject	Manual XTE SD (cm)	VSN XTE SD (cm)	Combined XTE SD (cm)	Combined Steering Adjustments (min^{-1})
S1	6.5 ±3.1	5.8 ±1.3	6.2 ±2.4	20 ±3
S2	5.2 ±0.4	3.4 ±0.0	4.3 ±1.0	28 ±2
S3	5.1 ±0.7	5.9 ±0.9	5.6 ±0.9	20 ±3
S4	6.6 ±1.7	6.6 ±1.9	6.6 ±1.8	21 ±3

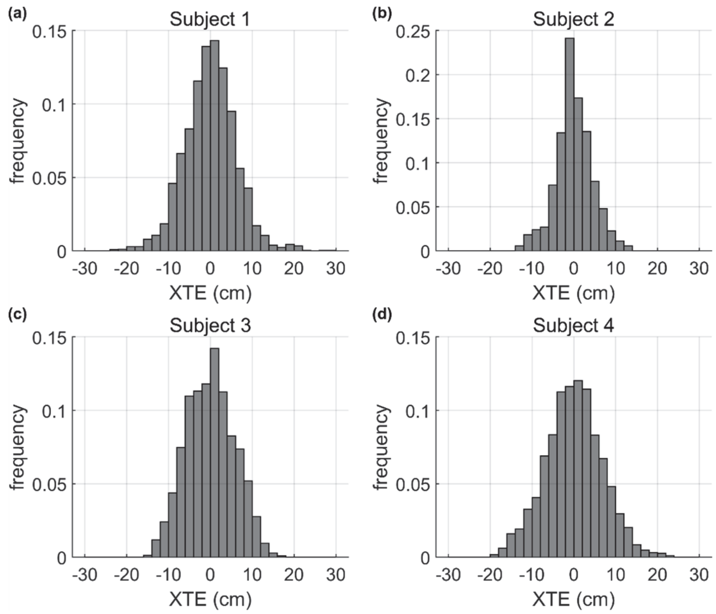

Figure 7. Histograms of XTE measurement frequency in 2 cm bins. Both steering types are included for each subject. There were 6226, 709, 9426, and 6938 data points for subjects 1 to 4, respectively.

Discussion

Sprayer Operator Stress

Our hypothesis was confirmed that using an automatic guidance system reduces agricultural sprayer operators' stress compared to when they are steering manually. The average operator experienced a significant reduction (48% lower, $p < 0.001$) in his stress rate while steering with VSN compared to when he was steering manually (fig. 4d), which helps explain previous reports that automatic guidance systems reduce operator stress and fatigue (Amiama Ares et al., 2011; Berglund and Buick, 2005; Billingsley and Schoenfisch, 1997; Kocher et al., 2000; Kviz and Kroulík, 2017). The stress rate reduction when steering with VSN compared to steering manually was double that of the reduction for automobile drivers' highway driving compared to city driving (24%, fig. 5b). This comparison is limited because a small number of different subjects participated in the two studies, but it provides context because most readers have experience that, due to fewer stimuli, automobile highway driving is less stressful than city driving.

No previous studies have reported the stress rates of self-propelled sprayer operators, although a previous study reported EDA measurements for tractor drivers. The tractor drivers wore wristbands and were instructed to keep the tractor as close to the center of an oval track as they could, but there was no significant difference in manual or guidance steering using a threshold of 0.02 μS (Dam et al., 2020). The results of that study may differ from what was found here because there is a continuous requirement for the sprayer operator to keep the wheels from damaging the plants when spraying in row crops. In the U.S., the vast majority of corn rows, and about a quarter to half of soybean rows, are on 76 cm (30 in.) spacing (USDA-NASS, 2021), and agricultural sprayer wheels are commonly 38 cm (15 in.) wide. This gives an operator 19 cm (7.5 in.) of space on each side of the wheel, which is not a large buffer, considering that North American operators commonly drive 20 to 29 km h^{-1} (12 to 18 mi h^{-1}) or faster (Burgers et al., 2021). The increased feedback of the crop row likely puts more pressure on the sprayer operator with more potential stressful events (e.g., crop damage could provide poor customer service, have negative financial consequences, and cause reputation damage) than driving a tractor on a track.

In this study, the subjects participated while working and thus were not exposed to known singular events of stress at known times, as would be done in a laboratory situation. In a field situation, there is no way to control the occurrence of stressful events. To mitigate this, data from multiple passes with each steering type were compared. Each subject chose when to participate and which passes to drive manually and which to drive with VSN. For each subject, both steering types were used in the same field so that other potentially confounding differences would be standardized; for example, the effect of sprayer type, time of day, operator experience, operator fatigue, waterways, hills, and tile drainage would be similar for each steering type for each subject.

The stress rates significantly differed between operators. Thus, an experiment like this must be performed with operators who drive both manually and with guidance. When the subjects were not wearing a wristband, they defaulted to VSN steering because it presumably allowed them to devote their attention to other aspects of their work. It is possible that those other aspects could have caused stressful events in this study, and when the operator was steering manually they were unnoticed or were addressed later. The scope of this study was not to differentiate between steering and non-steering stressful events.

Steering Performance

There are limited data on the performance and effect of fatigue on skilled agricultural operators (Batte and Ehsani, 2006), and the available data have been reported as percentage overlaps in the absence of row crops (Kaivosoja and Linkolehto, 2016; Lipiński et al., 2016; Shinners et al., 2010). This is the first study to report the steering performance of professional sprayer operators or vision or radar guidance on a sprayer (figs. 6 and 7, table 4), and it is especially useful because no other data are available for row crops at travel speeds that are representative of what North American operators drive today. The steering performance quantification reported here can be used to estimate how much wheel track damage occurs, in economic analyses (Batte and Ehsani, 2005, 2006; Weisz et al., 2011), and as a reference to compare the performance of automatic guidance systems (Bonadies and Gadsden, 2019; Xue et al., 2012).

Figure 8 shows vehicle XTE SD or root mean square deviation (XTE RMSD) reported in the literature (Fehr and Gerrish, 1995; Gan-Mor et al., 2007; Gerrish et al., 1997; Gomez-Gil et al., 2011; Hiremath et al., 2014; Tillett and Hague, 1999; Xue et al., 2012; Zhang

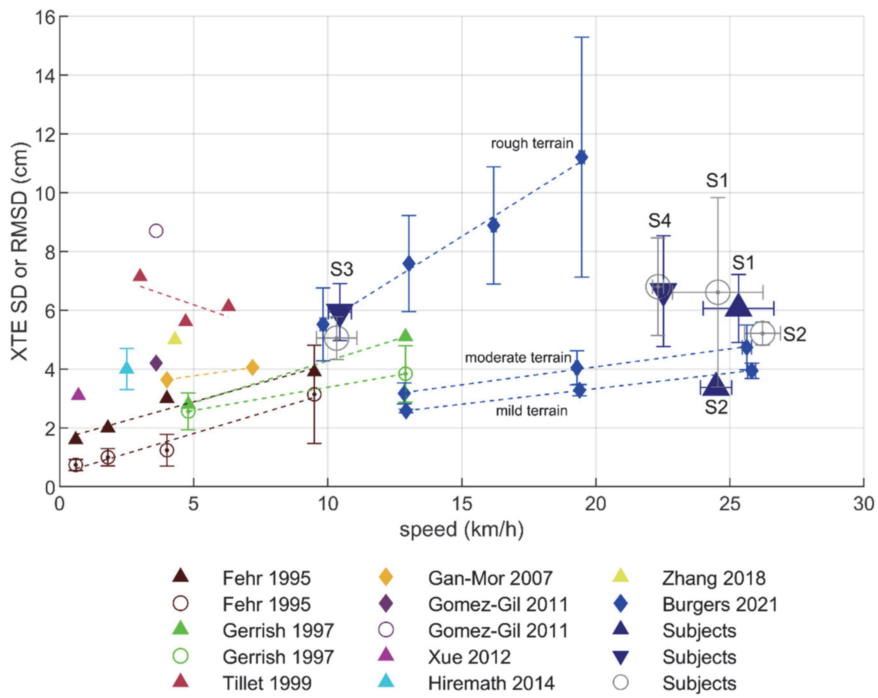

Figure 8. Steering performance by speed and steering type. Open circles are for manual steering, upward-facing triangles are for vision steering, diamonds are for GPS steering, and downward-facing triangles are for radar steering. Linear regression lines are shown on data that were collected over the same course at different speeds. Data are reported as XTE SD except for Gan-Mor et al. (2007), Xue et al. (2012), and Hiremath et al. (2014), who reported XTE RMSD. Error bars represent standard deviations when the reported data were collected over repeated passes on the same course (by different operators for manual steering). The three terrain roughness courses from Burgers et al. (2021) are indicated separately. Results from this study are indicated for each subject (S1 to S4) with error bars for the same subject. These error bars represent standard deviations of multiple, but not repeated, passes.

et al., 2018). See Burgers (2022a) for details on the referenced studies and Burgers (2022b) for plotted datasets. The method used in this study to calculate XTE SD from GPS coordinates was also used on the passes from GPS-guidance steering datasets (Burgers, 2021; Burgers and Gaard, 2021; Burgers et al., 2021). See Burgers (2022a) for details. Those data were collected in sprayers over three terrain roughness courses and at similar speeds as were reported here.

The steering performance from this study was marginally worse than the previously reported performance (fig. 8), but the degree of difficulty of operating a self-propelled sprayer was higher than in most of the previous studies. Except for one case (Burgers et al., 2021), the available performance data from the literature were collected from vehicles smaller than sprayers. A sprayer is less maneuverable (yaw) than a tractor due to its increased vertical axis moment of inertia from its wide boom. The subjects in this study drove considerably faster than in previous reports on smaller vehicles (fig. 8).

Because fatigue affects the performance of automobile drivers (Davenne et al., 2012) and airplane pilots (Morris and Miller, 1996), we hypothesize that there is some performance decay when steering manually over a longer duration than what was measured in this study. As described above, all subjects primarily drove with VSN when not participating in the study. While the subjects in this study likely experienced some fatigue from the stressful events experienced while operating with VSN, that fatigue was likely not as high as it would have been if they had instead driven manually (due to VSN's lower stress rate). Thus, the manual performance reported here was likely better than the manual steering performance of a typical fatigued operator.

Conclusions

Sprayer Operator Stress

Professional sprayer operators using a vision or radar guidance system (VSN) had on average a 48% lower stress rate than when they were steering manually. The use of an automatic guidance system such as VSN could have a dramatic positive effect on the health of sprayer operators, especially during the long workdays of the peak spraying season, and could reduce the negative effects that stress and fatigue have on steering performance, mistakes, and accidents. Future research is recommended to evaluate:

- Differences between male and female operators, between vision and radar (and GPS) steering, between front boom and rear boom sprayers, and between crop types.
- The effect of operator experience on the stress rate.
- Differences in stressful events from steering versus other job-related activities.
- The long-term effect of automatic guidance on the health of sprayer operators.

Steering Performance

The steering performance of professional sprayer operators and both vision and radar guidance was reported for the first time. There was no significant difference in the performance of the steering types. The steering performance reported in this study was marginally worse than the previously reported performance, but the degree of difficulty of operating a sprayer was higher than in most previous studies. The data can be used to estimate sprayer wheel track damage, in economic analyses, and as a reference to compare the performance of manual or other automatic guidance systems. Future research is recommended to quantify how fatigue that accumulates over the long workdays of the peak spraying season affects the steering performance of manual operators throughout a day or season.

Acknowledegements

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Conflict of Interest

Authors TAB, KJV, and KJV's husband (RV) are employees of Raven Industries. Raven Industries funded this study. KJV and RV previously owned Raven stock. TAB has patents (granted or pending) for which Raven Industries is the assignee but none related to Raven's patents for the VSN system. TAB and KJV have personal aversions to the negative effects of stress.

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Nomenclature

EDA = Electrodermal activity
RMSD = Root mean square deviation
SCL = Skin conductance level
SCR = Skin conductance response
VSN = Raven Industries' vision and radar guidance system
XTE = Cross-track error
XTE SD = Cross-track error standard deviation