An Automated On-The-Go Unloading System Reduces Harvest Operator Stress Relative to Manual Operation

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Research

HIGHLIGHTS

- Stress was measured in harvest operators who performed on-the-go unloading manually and with an automated system.
- Automated unloading reduced the average grain cart and combine operator stress rate by 18% and 12%, respectively, compared to manual operation.
- Harvest operators usually worked more than 9 hours and often worked more than 12 hours per workday during harvest.
- The use of automated unloading systems could positively affect the health of harvest operators.

ABSTRACT. *On-the-go unloading improves harvest operational efficiency, but it requires skilled labor because it is challenging and stressful to balance numerous concurrent tasks. Harvest automation reduces workload, stress, and fatigue. The objective of this study was to determine if using a commercially available, automated on-the-go unloading system (Raven Cart Automation™, RCA, Raven Industries) would reduce operator stress compared to manual operation. Nine grain cart tractor operators and six combine operators participated in this study. Operators performed their typical harvest operation, except to alternate on-the-go unloading using RCA or operating manually. Skin conductance (electrodermal activity) was measured with an Empatica E4 wristband, and stressful events were quantified. Machine data was collected from the tractor and combine via CAN logs. Over 200 total unload events were analyzed. Grain cart and combine operators using RCA had an 18% ($p = 0.022$) and 12% ($p = 0.18$) reduction in stress rate, respectively, compared to operating the grain cart tractor manually. RCA reduced the tractor cross-track error standard deviation by 2.5 cm on straight passes ($p < 0.0001$). The use of an*

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automated on-the-go unloading system reduces operator stress during harvest and could positively affect the health of operators, especially during the long harvest workdays.

Keywords. *Agricultural workers, Combine operators, Custom harvesters, Electrodermal activity, Grain cart operators, Guidance systems, Harvest, Skin conductance, Stress, Vehicle automation.*

Those working in harvest operations—farmers in their own crops or custom harvesters in others' crops—work long, stressful days. In North America, custom harvest crews harvest from Texas as early as April, make their way through the grain belt in summer, and end in Canada (Steffen et al., 2007). Then those crews harvest fall crops through November or December (Holcomb, 2022). These crews average 6.5 workdays per week; over half work 12–14 hours per day, and another third work 9–11 hours per day (Steffen et al., 2007).

For harvest crews, properly managing the logistics of the operation is key to its efficiency. Commonly, a combine harvests and gathers the grain into a hopper. A tractor pulling a grain cart supports the combine to allow it to focus on harvesting and gathering. The combine's hopper fills, and the combine unloads into the grain cart. The grain cart fills, and the tractor takes the grain cart to unload it into a stationary semi-trailer. If the grain cart is unavailable when the combine's hopper is full, the combine is forced to stop harvesting and wait to unload. The harvesting job is completed more efficiently the fewer times the combine stops.

On-the-go unloading—when the grain cart matches speed with the combine, which unloads while moving—improves harvest efficiency because it is much faster than if the combine stops to unload (Delchev et al., 2016). But on-the-go unloading is challenging (Liu et al., 2022) and stressful. It also requires high-skilled labor for both the combine and grain cart tractor operators (Liu et al., 2022), because there are a number of tasks that need to be performed concurrently (Bennett et al., 2015; Du et al., 2016; Liu et al., 2022). Operators monitor the position of the auger above the grain cart, grain cart fill level, machine speed, machine performance, and crop harvesting conditions and settings. This task complexity adds to operator stress (Du et al., 2016) and fatigue (Bennett et al., 2015; Nicholls et al., 2004). Additionally, all this happens in close proximity (see fig. 1) to expensive equipment (e.g., a US $1 million combine and header (Holcomb, 2022)). To avoid damage, which is more likely with inexperienced operators (Holcomb, 2022), the operators have to maintain communication (Du et al., 2016).

To exacerbate the need for highly-skilled labor, the cost of labor is increasing (Shangguan et al., 2021); for example, nonsupervisory hourly (inflation-adjusted) wages increased by about 6% from 2014 to 2017, which was larger than the nonfarm wage increase (Zahniser et al., 2018). There is also a shortage of skilled labor (Holcomb, 2022; Shangguan et al., 2021). In the US, H-2A (agricultural) seasonal guest workers can only be hired if farmers demonstrate they cannot fill the jobs with domestic workers (Charlton and Castillo, 2021). The number of all H2-A workers tripled from 2011 to 2019 (Charlton and Castillo, 2021), and the number of H2-A field laborers doubled in that time (Castillo et al., 2021). These increases indicate a tightening labor market because H-2A workers account for 10% of the total US farmworkers (Costa and Martin, 2020).

Automation such as steering (Benson, 2001; Du et al., 2016; French Jr., 2013) and on-the-go unloading (Liu et al., 2022) helps workers by reducing workload (Bennett et al.,

Figure 1. Photograph from the combine of an on-the-go unload event in wheat. Note the close proximity of the grain cart to the combine header.

2015), stress (Du et al., 2016), and fatigue (Bennett et al., 2015; French Jr., 2013). Raven Cart Automation^{TM} (RCA; Raven Industries, Inc., an affiliate of CNH Industrial N.V., Sioux Falls, SD) is a commercially available system that controls the grain cart speed and steering (and thus cart positioning) to synchronize it with the combine and assist operators during on-the-go unloading.

The objective of this study was to determine if using a commercially available, automated on-the-go unloading system (RCA) would reduce operator stress compared to manual operation. Because the harvest operation is stressful and automation reduces stress and fatigue, our hypothesis was that RCA reduces combine and grain cart operator stress compared to manual grain cart operation.

Materials and Methods

Participants and Protocol

Subjects were recruited from the group of Raven Industries customers who participated in limited release (beta) RCA product testing. Twenty-eight combine and grain cart tractor operators (27 males and 1 female) enrolled in this study. The research protocol was approved by the South Dakota State University Institutional Review Board, and each subject consented to his or her involvement before participating. Subjects were instructed to perform their typical harvest operation, except to alternate on-the-go unloading using RCA or operating the grain cart tractor manually about every hour. Investigators snugly fit an Empatica E4 wristband (Empatica Inc., Boston, MA) to each subject. Fifteen subjects were removed by the investigators because they did not wear a wristband or they did not perform at least three unload events in the same day both with RCA and manually; specifically, one subject's site was not visited and he did not wear the wristband, six subjects at one site did not use RCA because of a software bug (which was later resolved), two subjects only operated combines that did not have RCA installed, one subject's wristband had data collection issues and did not collect valid data that day, three subjects only used RCA for unload events, one subject only had two manual on-the-go unload events, and one subject did only manual unloads on one day and only RCA unloads on another day. The 13 male participating subjects and their machine information are listed in table 1 (two operated both the combine and tractor). Figure 2 shows aerial photographs of two representative harvest operations.

Data Collection

For estimation of operator–machine usage, grain cart tractor telematics messages (which included speed, RTK-GPS, and RCA metrics) were collected at an interval of 1 s. For other analyses, machine CAN logs (which included speed, RTK-GPS, RCA metrics, and the combine auger status) were acquired from each participant's machine (RS Lite™, Raven Industries). System measurements were parsed from CAN logs at an interval of 0.6 s. Skin conductance (electrodermal activity, EDA) data from the wristband was collected at 4 Hz. EDA data was imported and processed in MATLAB R2022b (MathWorks, Natick, MA). CAN, EDA, and telematics data were processed in Jupyter notebooks using Python 3.10.

Machine Measurements

A local *x-y* coordinate system for each harvest operation was calculated from CAN-based GPS latitude and longitude using a haversine equation and great circle distances (Daidzic, 2017; Tsai, 2011) according to the method of Burgers and Vanderwerff (2022).

The start and end of on-the-go unload events were identified based on when the combine auger turned on and off. For each unload event, the automation type was recorded from

Table 1. Subjects and equipment information.

Subject[a]	Operator Experience with Machine Type (years)	Machine	Region[b]	Crop[c]	Harvest Date(s) (2023)
GC1	3	Case IH Magnum 340	Northeast Colorado	Wheat	26 and 27 July
GC2	3	Case IH Magnum 340	Northeast Colorado	Wheat	27 July
GC3	1	Case IH Magnum 340	Central Montana	Wheat	1 and 3 August
GC4	5	Case IH Magnum 340 Case IH Steiger 420	Central Montana Northwest Iowa	Wheat Corn	1 and 3 August 6 November
GC5[d]	18	Case IH Magnum 380	Northern Oklahoma	Corn	13 September
GC6[e]	40	Case IH Magnum 380	Northern Oklahoma	Corn	14 September
GC7	15	Case IH Magnum 380	Northern Oklahoma	Corn	14 September
GC8	10	Case IH Magnum 380	Northern Oklahoma	Corn	14 September
GC9	7	Case IH Magnum 310	Western Tennessee	Soybeans	18 and 19 October
C1	11	Case IH 8250	Northeast Colorado	Wheat	26 and 27 July
C2	5	Case IH 8250	Northeast Colorado	Wheat	26 and 27 July
C3	30	Case IH 8250	Central Montana Northwest Iowa	Wheat Corn	1 and 3 August 6 November
C4[e]	40	Case IH 8250	Northern Oklahoma	Corn	13 and 14 September
C5[d]	16	Case IH 8250	Northern Oklahoma	Corn	14 September
C6	6	Case IH 7250	Western Tennessee	Soybeans	18 and 19 October

[a] GC is grain cart operator, C is combine operator; the number gives the operator ID for each group.
[b] The combine:grain cart tractor ratio was 4:1 in Colorado (but only two combines and the tractor had RCA), 1:1 in Montana, 2:2 in Oklahoma (but only one combine and one tractor had RCA), 1:1 in Iowa, 3:1 and 2:3 in Tennessee (but only two combines and two tractors had RCA).
[c] Custom harvest crews were harvesting in Colorado and Montana. Farmers were harvesting their own crops in Oklahoma, Iowa, and Tennessee.
[d] GC5 and C5 were the same operator.
[e] GC6 and C4 were the same operator.

Figure 2. Aerial photographs of representative on-the-go unload events in corn with (a) Case IH 8250 and Magnum 310 and (b) New Holland CR8.90 and T8.

CAN messages from the RS Lite, and the average speed, duration, and distance of the unload event were calculated.

The cross-track error (XTE) for both the combine and tractor was calculated for each unload event by fitting a linear regression line to each machine in the *x*-*y* coordinate system following the method of Burgers and Vanderwerff (2022). Steering performance was quantified as the standard deviation of the XTE (XTE SD) of the on-the-go unload event.

EDA Measurements and Stressful Events

EDA data was processed according to a series of filters (Jebelli et al., 2019; Kleckner et al., 2017) and quality checks (Kleckner et al., 2017) according to the methods of Burgers and Vanderwerff (2022). Stressful events were defined as those with a minimum threshold of 0.01 μS (Caruelle et al., 2019; Lajante et al., 2012) and a duration of 1–3 s (Dawson et al., 2011; Lajante et al., 2012). Wristband and CAN time were aligned via UTC time. The number and rate of stressful events were calculated for each on-the-go unloading event (see MATLAB Figshare link in the Supplemental Materials section).

Operator−Machine Usage

Grain cart tractor telematics message data was processed from two machines to determine daily operator−machine usage over two peak harvest periods (July for small grains and October/November for corn and soybeans). A day was considered from 6 a.m. to 6 a.m. local time to account for instances operators worked past midnight. Slow, medium, and fast times were defined as the duration the tractor was moving according to the speed ranges in table 2 and represent the approximate speeds for unloading, in-field transit, and road transit, respectively. Stationary time occurred between the first and last moving times of the day. The distance traveled between telematics messages was calculated using the GPS positions and timestamps of consecutive messages. The sum of slow, medium, fast, and stationary times and the sum of distance traveled each day were calculated. A workday was defined as one with more than one hour in the non-stationary categories during a day. Note that the data collection period for operator–machine usage was done remotely with telematics messages, and the period for stress collection was done on-site for at most two days. The overlap between operator–machine usage period and stress collection period occurred when GC1 and GC2 operated one machine during on-site stress testing in July and GC4 operated the other machine during on-site stress testing in November.

Summary Metrics and Statistics

The mean stress rate (e.g., stressful events/min) was calculated as the duration-weighted average of the unload events, which is the total number of events divided by the total time for each steering type for each subject (i.e., they were not averaged per unload event because unload events were not all the same duration). The subject-normalized stress rate was calculated as each unload event stress rate divided by the manual mean stress rate for that operator (for the two operators in different crops (see table 1), the overall mean rate for both crops was used). Means for XTE SD were averaged per unload event.

Two-way analysis of variance (ANOVA) tests were performed on the response variables with automation type (RCA or manual) and subject as categorical variables (Minitab 21, Minitab, LLC, State College, PA), and $p < 0.05$ considered significant. Regression analyses were performed to test if grain cart and combine operator normalized stress rates were predicted by tractor XTE SD and automation type, and if tractor XTE SD was predicted by combine XTE SD, automation type, and tractor speed. When driving straight, the combine typically used GPS to control steering, so these regression analyses were performed only on straight unload events (defined as combine XTE SD < 10 cm and tractor XTE SD < 30 cm). Box-Cox data transformations were applied when the data was not normally distributed.

Results and Discussion

Results

Operator–Machine Usage

The operator–machine usage of two system tractors is shown in figure 3. In July, two custom harvest crews (T1 and T2, table 3) harvested small grains. In October, one custom crew (T1, table 3) harvested corn and soybeans, and from October to November, one local

Table 2. Grain Cart Tractor Speed Categories.

Speed Category	Speed Range (m/s)	Speed Range (km/h)	Speed Range (mi/h)
Stationary	< 0.2	< 0.7	< 0.4
Slow	0.2–5	0.7–18	0.4–11
Medium	5–10	18–36	11–22
Fast	> 10	> 36	> 22

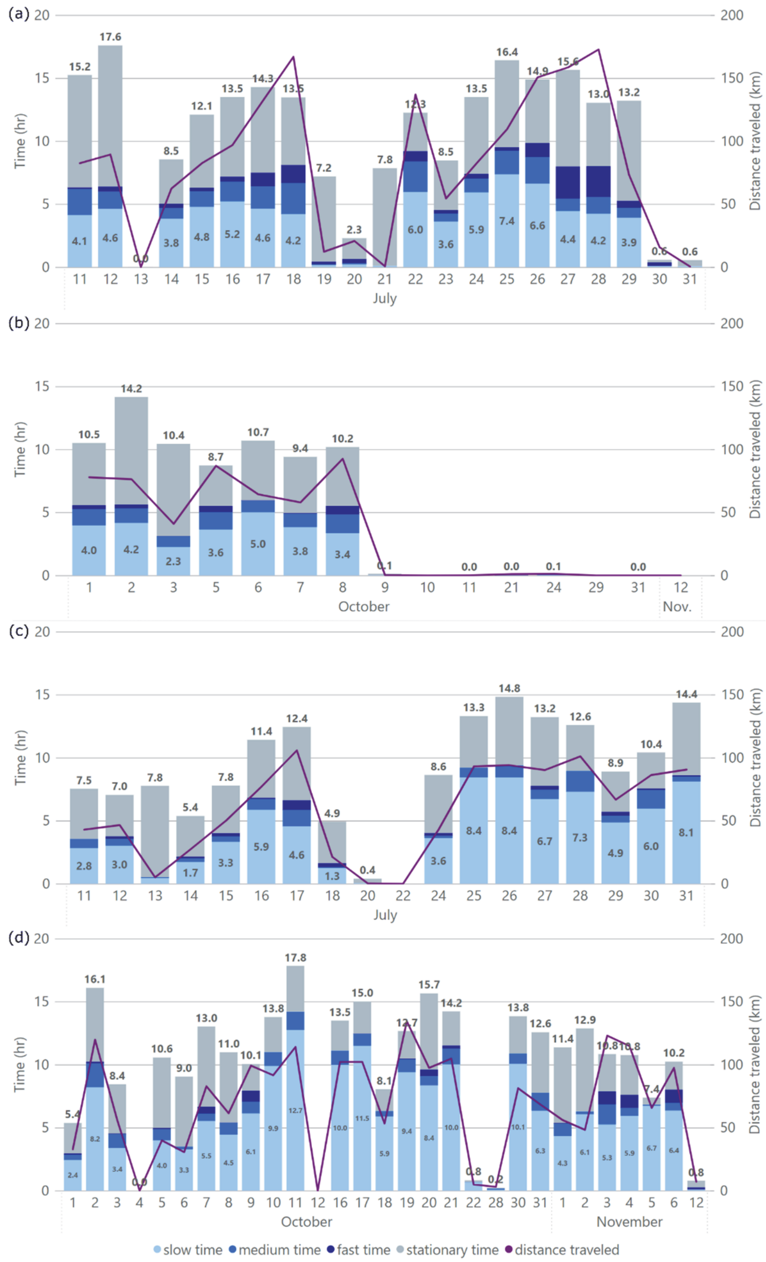

Figure 3. Operator−Machine usage (time and distance) for (a) T1 in July, (b) T1 in October, (c) T2 in July, and (d) T3 in October and November. Times (stacked bar chart) are plotted on left axis, and distance (line) is plotted on right axis. The data label on the top of the bar is the sum of the moving and stationary times for the day; the data label on the slow time bar is the slow time for the day. T1 was the Case IH Magnum 340 used by GC1 and GC2 in July (Colorado) and October (Nebraska), T2 was the Case IH Magnum 340 used by GC4 in July (Montana), and T3 was the Case IH Steiger 420 used by GC4 in October and November (Minnesota and Iowa); all were using RCA.

Table 3. Operator−Machine usage.

Machine ID	Month	Machine	Grain Cart Operator[a]	Harvest Crew	Work-Days[b]	Workdays > 9 h (% workdays)	Workdays > 12 h (% workdays)	Average workday distance (km)
T1	July	Case IH Magnum 340	GC1, GC2	Custom harvest	15	13 (87%)	13 (87%)	110
T1	Oct	Case IH Magnum 340	GC1, GC2	Custom harvest	7	6 (86%)	1 (14%)	71
T2	July	Case IH Magnum 340	GC4	Custom harvest	15	8 (53%)	6 (40%)	69
T3	Oct, Nov	Case IH Steiger 420	GC4	Local farmer	24	20 (83%)	12 (50%)	82

[a] Grain cart operator (see table 1) in machine during stress portion of the study.
[b] Workday had > 1 hour in motion (see table 2).

farmer (T3, table 3) harvested corn and soybeans. Both the custom harvest crews and the local farmer usually worked >9 hours per day, often >12 hours per day, and twice worked more than 17 hours in a single day (fig. 3, table 3). The tractors averaged 69–110 km (43–68 mi) per workday (table 3). Plotted datasets can be found in the Supplemental Material section.

Stress

Grain Cart Operators

For the nine grain cart operators, 233 on-the-go unload events were analyzed. The operators had a significantly lower stress rate when using RCA than when operating manually (1.29 fewer stressful events/min, 4.35 vs. 5.64 stressful events/min, $p = 0.022$, 95% CI of -2.38 to -0.19, fig. 4a). There was also a significant difference in the stress rate between operators ($p < 0.0001$), so subject-normalized stress rates are shown by operator in figure 4b. Box plots of these stress rate measures are shown in figure 5. The subject-normalized RCA means are shown by operator experience in figure 6; eight of the nine operators had a stress rate decrease when using RCA relative to operating manually. The nine operators on average had an 18% lower stress rate when unloading with RCA than manually (range of 54% reduction to 11% increase, figs. 4b and 6). Operator experience did not predict the subject-normalized stress rate ($p = 0.6$). Plotted datasets can be found in the Supplemental Material section.

Combine Operators

For the six combine operators, 210 on-the-go unload events were analyzed. The combine operators had a lower stress rate when using RCA than when the grain cart tractor was operating manually (0.66 fewer stressful events/min, 2.67 vs. 3.33 stressful events/min, 95% CI -1.63 to 0.32, fig. 7a), but this difference was not significant ($p = 0.18$). There was a significant difference in the stress rate between operators ($p < 0.0001$), so subject-normalized stress rates are shown in figure 7b. Box plots of these stress rate measures are shown in figure 8. The subject-normalized RCA means are shown by operator experience in figure 9; four of the six operators had a stress rate decrease when RCA was used relative to the grain cart tractor operating manually. The six operators on average had a 12% lower stress rate when unloading with RCA than manually (range of 75% reduction to 49% increase, figs. 7b and 9). Operator experience did not predict the subject-normalized stress rate ($p = 0.7$). Plotted datasets can be found in the Supplemental Material section.

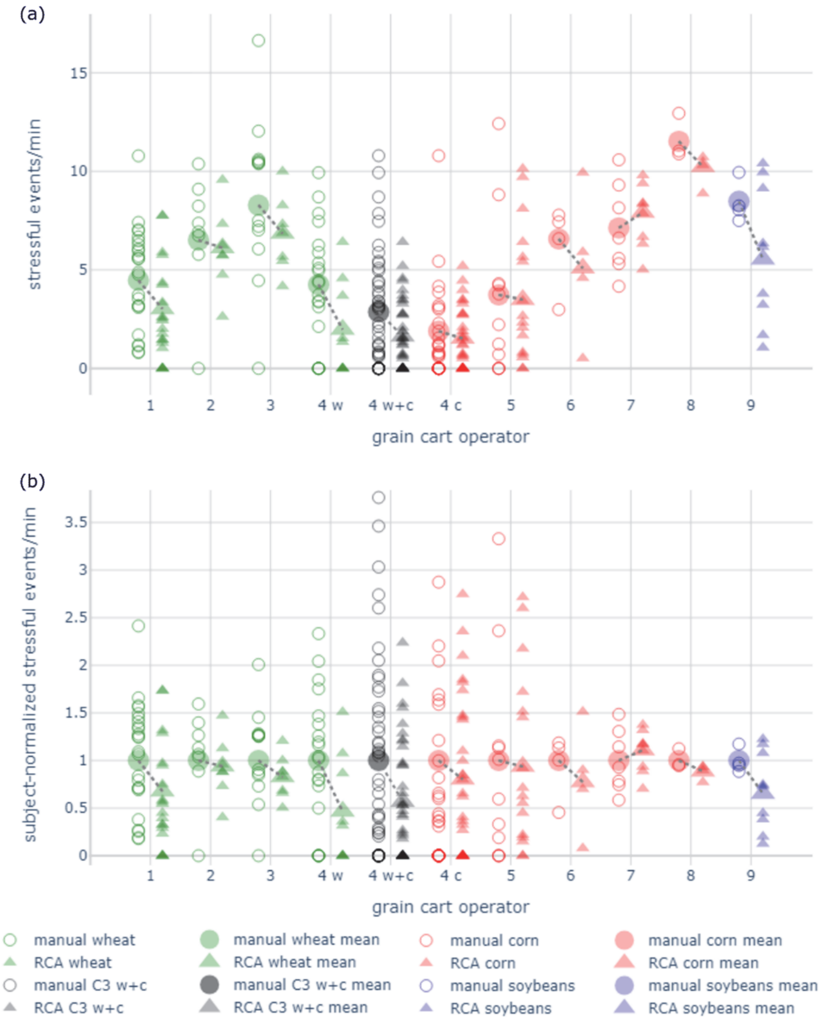

Figure 4. Individual value plot of (a) stress rate per grain cart operator and (b) stress rate normalized per each grain cart operator's manual mean (but note one manual point for 4c at 5.70 was removed from the graph for an improved y-axis scale). Each small shape represents the measurement from one on-the-go unload event, and each large shape represents the automation type (RCA and manual) weighted mean for each subject. Green indicates wheat, red indicates corn, blue indicates soybeans, and gray indicates Grain Cart Operator 4 (GC4) combined (w+c) in wheat (w) and corn (c).

Tractor XTE SD

Tractor XTE SD Regression

During 201 straight on-the-go unload events (combine XTE SD < 10 cm and tractor XTE SD < 30 cm), the use of RCA significantly reduced tractor XTE SD by 2.5 cm compared to manual operation ($p < 0.0001$, fig. 10), but combine XTE SD and tractor speed were not significant predictors ($p = 0.28$ and 0.24, respectively) in the regression analysis. Plotted datasets can be found in the Supplemental Material section.

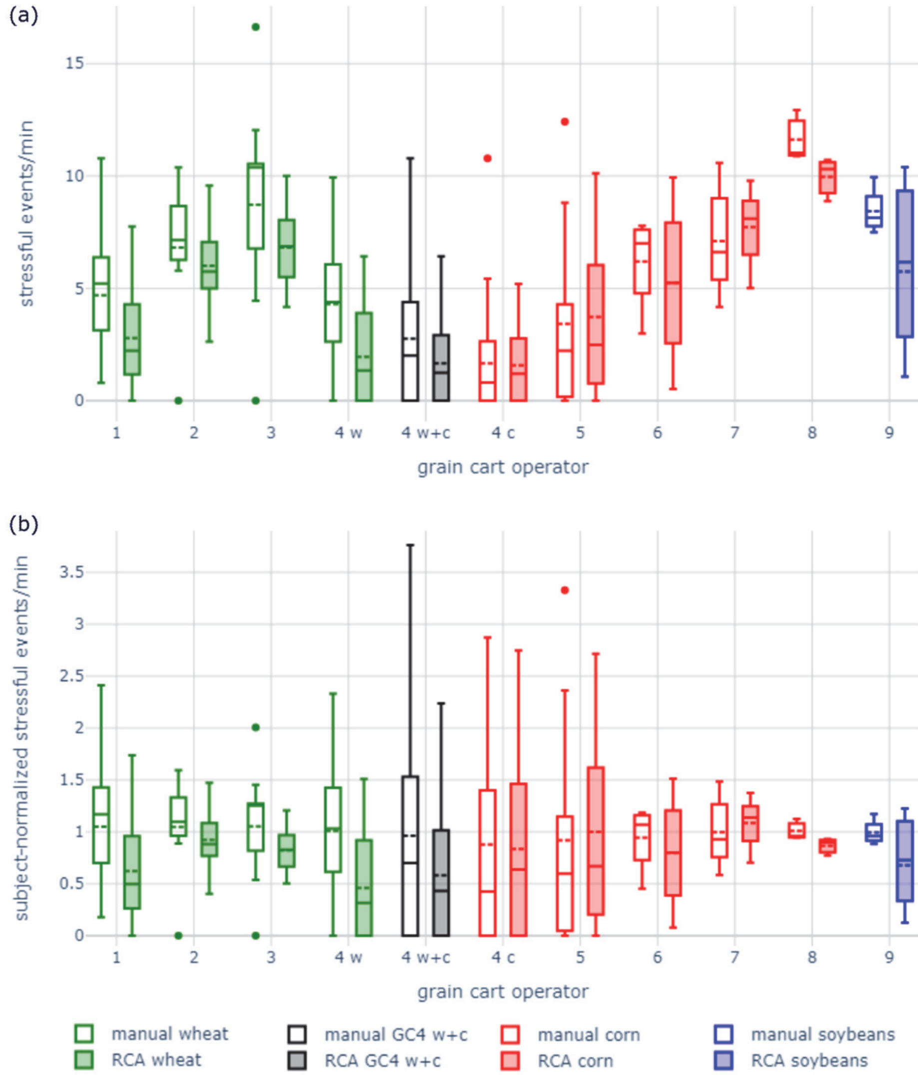

Figure 5. Box plot of (a) stress rate per grain cart operator and (b) stress rate normalized per each grain cart operator's manual mean (but note one manual point for 4c at 5.70 was removed from the graph for an improved y-axis scale). Green indicates wheat, red indicates corn, blue indicates soybeans, and black indicates Grain Cart Operator 4 (GC4) combined (w+c) in wheat (w) and corn (c). The solid and dotted lines in each box are the median and mean of the non-weighted stress rates, respectively.

Stress Regression

During 194 straight on-the-go unload events (combine XTE SD < 10 cm and tractor XTE SD < 30 cm), grain cart normalized stress rate was not significantly predicted by tractor XTE SD ($p = 0.98$) or automation type ($p = 0.18$) in a regression analysis.

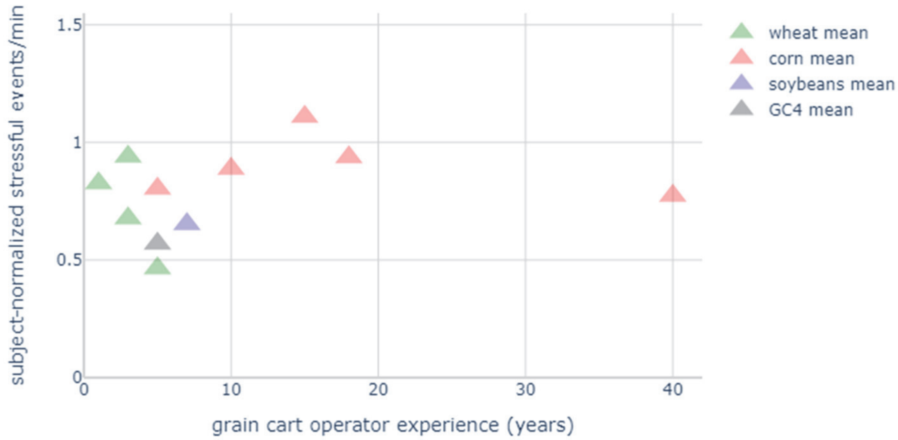

Figure 6. Subject-normalized mean stress rate per grain cart operator's experience. Green indicates wheat, red indicates corn, blue indicates soybeans, and gray indicates Grain Cart Operator 4 (GC4) combined in wheat and corn.

During 181 straight on-the-go unload events (combine XTE SD < 10 cm and tractor XTE SD < 30 cm), combine normalized stress rate was not significantly predicted by tractor XTE SD ($p = 0.27$) or automation type ($p = 0.28$) in a regression analysis.

Discussion

Operator–Machine Usage

During the harvest season, crews work long, stressful days to harvest crops. For the two harvest crews that were monitored, the crews usually worked more than 9 hours per day and twice worked more than 17 hours in a day (fig. 3, table 3). The observed behavior of the custom harvest crews is consistent with the 9–14 hours per day previously reported (Holcomb, 2022; Steffen et al., 2007). Note that the grain cart operator is often working even when the grain cart is stationary; for example, during this time the grain cart unloads into the semi-trailer, loads are tracked per field, and the grain cart operator could be waiting for a combine to turn around or be evaluating which combine to unload first. The operator–machine usage captures the amount of time between when the machine started moving and stopped moving, but the operators also work outside those hours (Doungpueng et al., 2020); for example, preparing the machine and operation at the beginning of the day; cleaning up at the end of the day; and preparing machines for transport, which can include putting the header on a trailer and cleaning the system for state line crossings. Thus, the hours reported here are likely a lower bound for the hours worked by these two harvest crews.

Stress

Our hypothesis was confirmed that an automated on-the-go unloading system (RCA) reduces grain cart and combine operator stress compared to manual operation, though the difference was only to the level of statistical significance for the grain cart operators. The stress rate reduction for the average operator (each operator was weighted equally despite the different number of unload events) was on average 18% for grain cart (fig. 4b) and 12% for combine (fig. 7b) operators, relative to when the grain cart tractor was operated manually during unloading. For some context, this difference is slightly less than the approximate 24% reduction that automobile drivers experience in highway driving relative to city

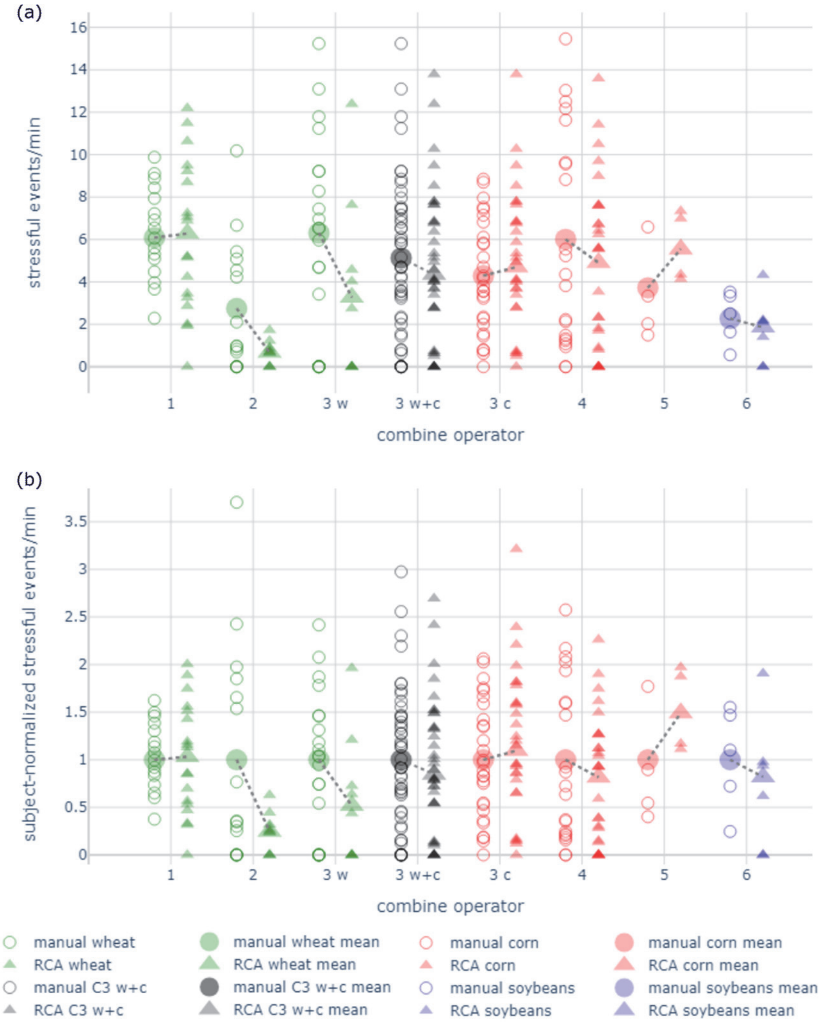

Figure 7. Individual value plot of (a) stress rate per combine operator and (b) stress rate normalized per each combine operator's manual mean. Each small shape represents the measurement from one on-the-go unload event, and each large shape represents the automation type (RCA and manual) weighted mean for each subject. Green indicates wheat, red indicates corn, blue indicates soybeans, and gray indicates Combine Operator 3 (C3) combined (w+c) in wheat (w) and corn (c).

driving (Burgers and Vanderwerff, 2022; Healey and Picard, 2005; Liu and Du, 2018; Ollander et al., 2016).

There have previously been no reports on the stress rates of harvest operators, though there has been some work with self-propelled sprayer operators and tractor drivers on a track. Sprayer operators experienced a 48% reduction in stress when using automated guidance in 76-cm (30-inch) crop rows (Burgers and Vanderwerff, 2022). There was no significant difference in guidance type for the tractor drivers (Dam et al., 2020), but those drivers were instructed to drive near the center of an oval track. Due to the proximity of the grain

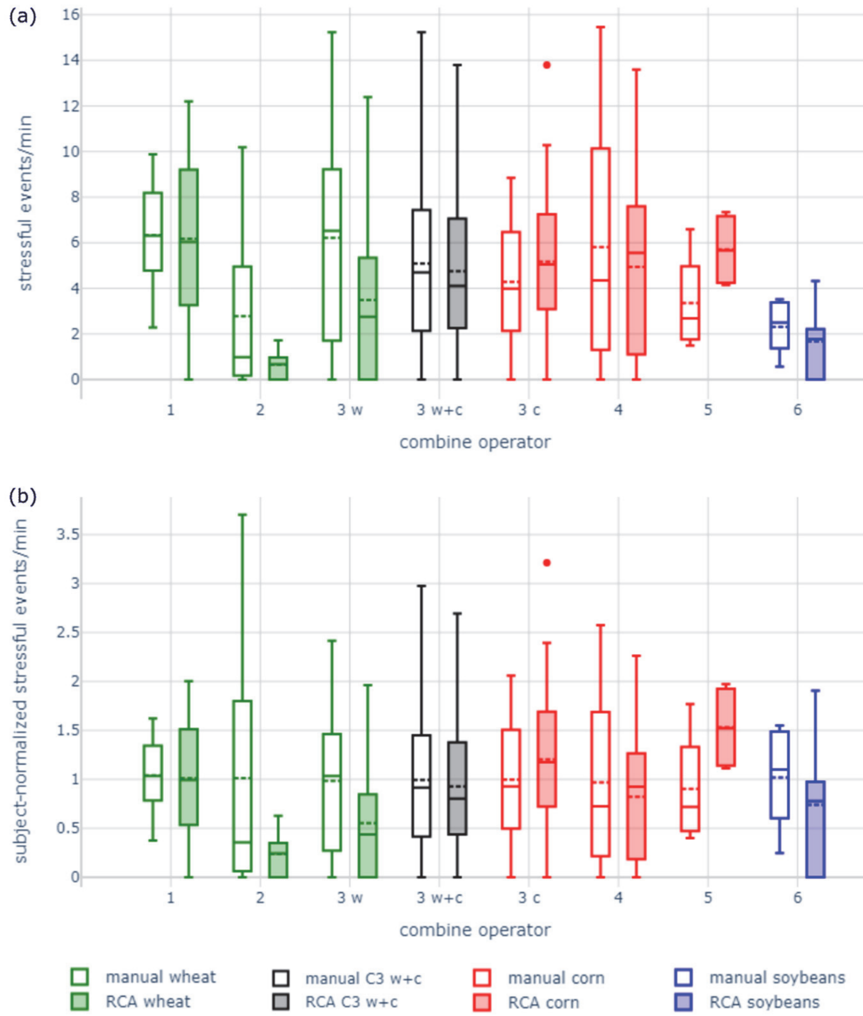

Figure 8. Box plot of (a) stress rate per combine operator and (b) stress rate normalized per each combine operator's manual mean. Green indicates wheat, red indicates corn, blue indicates soybeans, and black indicates Combine Operator 3 (C3) combined (w+c) in wheat (w) and corn (c). The solid and dotted lines in each box are the median and mean of the non-weighted stress rates, respectively.

cart to the combine, it is likely more stressful for both grain cart and combine operators to execute on-the-go unloading than track driving without close obstacles. Potential stressful events for harvest operators could include the movement of their own machine, the movement of other harvesting machines, changing field conditions, unforeseen obstacles, machine performance issues, communications via their own phone or radio from the crew, or a lack of trust in the technology.

Even though the automated system did not significantly reduce combine operator stress rate, four out of six operators had a stress rate reduction. Of the two who had increases in stress rate, Combine Operator 1 (8% stress rate increase, fig. 9) led a custom harvest crew

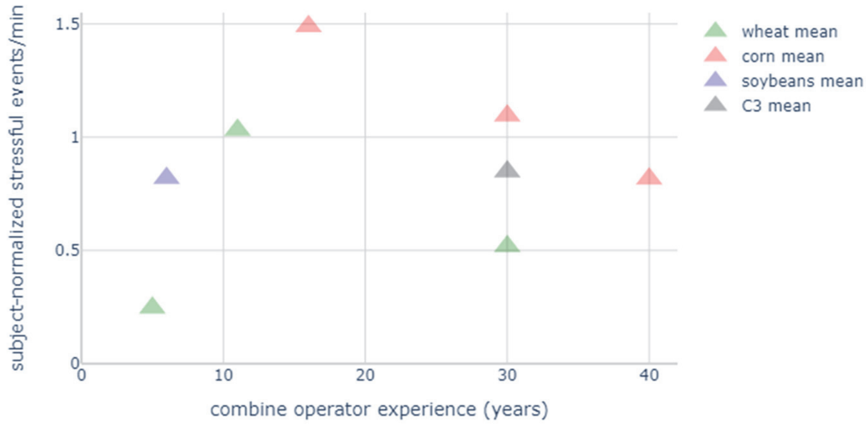

Figure 9. Subject-normalized mean stress rate per each combine operator's experience. Green indicates wheat, red indicates corn, blue indicates soybeans, and gray indicates Combine Operator 3 (C3) combined in wheat and corn.

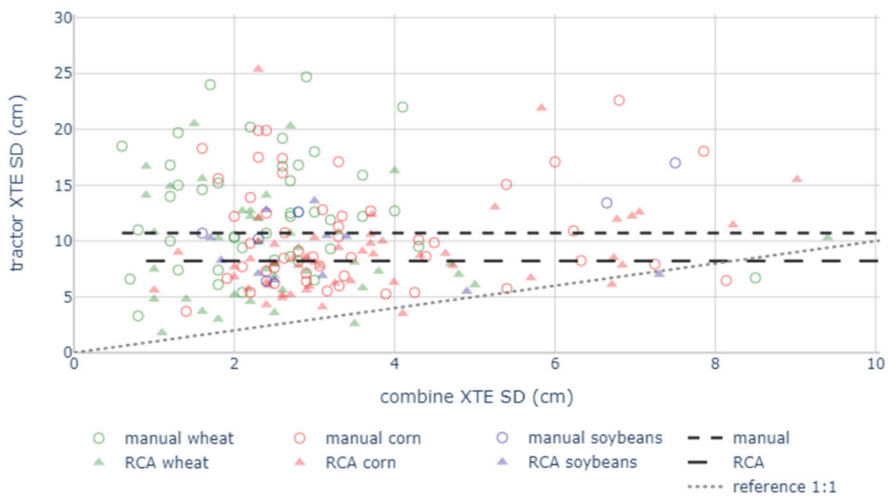

Figure 10. Individual value plot of tractor XTE SD versus combine XTE SD during straight on-the-go unload events (combine XTE SD < 10 cm and tractor XTE SD < 30 cm). Each shape represents the measurement from one unload event. Green indicates wheat, red indicates corn, and blue indicates soybeans. The dashed lines indicate the transformed regression equation for each automation type (short dash manual, long dash RCA). The dotted line is a reference 1:1 line between tractor XTE SD and combine XTE SD. RCA reduced the tractor XTE SD by 2.5 cm compared to manual operation.

of about a dozen workers. During his time in the study, he directed local work, coordinated with his remote boss, and managed two damaged combine incidents. Combine Operator 5 (49% stress rate increase, fig. 9) was the same as Grain Cart Operator 5, but on the day he drove the combine, he did not drive the tractor. He managed the movement of the center pivots in the fields they harvested and was involved in coordinating where the 18 semi drivers (employees and contractors) were to transport the corn (some to a local elevator, some to the family bins). Also, Combine Operator 3 (overall 15% decrease, fig. 9) had a

10% increase in corn, but he had a 48% decrease when operating with the same grain cart operator in wheat three months earlier.

In this study, grain cart and combine operators were not exposed to prescribed singular stress events as would be done in a laboratory setting (e.g., irritating but not painful electrical shock, air blast to throat, short loud noise through headphones (Leuchs et al., 2019)). During harvest, the occurrences of stressful events cannot be controlled. To reduce the impact of this, multiple on-the-go unload events for each automation type were compared. For each subject, both automation types were used in the same field on the same day, so that potential confounding differences would be as consistent as possible. For example, the effects of machine, speed, time of day, operator experience, operator fatigue, and field variation would be similar for each automation type for each subject. Thus, it was assumed that on-the-go unload events were relatively similar for each automation type.

While more than 200 on-the-go unload events that met the criteria were sufficient to measure a significant difference in grain cart operator stress, the number of operators did limit some of the conclusions. A limitation of this study was that with only nine grain cart and six combine operators, no relationship could be established on the effect of operator experience on operator stress rate. Another limitation was that all our participating subjects were males. The only female who did enroll did not complete at least three unload events, both with RCA and manually, and no other site had any female operators who could potentially enroll; this exemplifies the skew of male operators in harvest operations. Another limitation is that all the participants came from a group that was selected for product beta testing. This could potentially bias the participants as those with a favorable view of the company's products or as those who are more technologically adept than the general agricultural population. However, it is uncertain to what degree a participant's views of the technology, product, or manufacturer would increase or decrease his or her response to stressful stimuli, and while RCA includes advanced technology, the user interaction with the system is two simple button pushes on the multifunction handle, like engaging steering on agricultural machines.

Tractor XTE SD

During harvest, the combine operator typically uses GPS to control steering and the grain cart must match the combine's speed while maintaining a close position. The use of automation (RCA) during unloading reduced the tractor XTE SD by 2.5 cm during straight on-the-go unload events (fig. 10). The automation type and tractor XTE SD did not correlate with either the combine or grain cart operator normalized stress rate. The reduction in tractor XTE SD showed that automation successfully executed tractor steering. During unloading the grain cart is positioned in front of the combine so the operator must turn around to look at the combine and the position of the unloading grain (fig. 11). Despite this improvement in steering performance, tractor XTE SD was not a significant predictor of normalized operator stress.

Conclusions

Professional harvest operators work long, stressful days during the harvest season; they usually work more than 9 hours per day and twice worked more than 17 hours in a day (fig. 3, table 3). When they used an automated on-the-go unloading system (RCA), they had on average an 18% and a 12% lower stress rate (grain cart and combine operators, respectively) than when the grain cart tractor was operating manually. The use of an

Figure 11. Photograph from front of tractor of grain cart operator (not study participant) during stationary unload event. Using RCA, the operator can continually look back at the combine and the grain cart but does not hold the steering wheel (bottom right) because RCA controls steering and matches the combine's speed.

automated system such as RCA could positively affect the health of harvest operators, especially when accumulated over the long workdays of the peak harvest season. Future research is recommended to evaluate differences between male and female operators, differences between crop types, differences in operator technological ability, differences in operator age, and the long-term effect of automated on-the-go unloading systems on the health of harvest operators.

The use of automation (RCA) during on-the-go unloading reduced the tractor XTE SD by 2.5 cm during straight on-the-go unload events, but the automation type and tractor XTE SD did not correlate with either the combine or grain cart operator normalized stress rate.

Supplemental Material

The supplemental materials mentioned in this article are available for download from the ASABE Figshare repository at: https://doi.org/10.13031/26319289 (Supplemental Data) and https://doi.org/10.13031/26319364 (MATLAB).

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Conflict of Interest

All authors are employees of CNH Industrial (formerly Raven Industries). Raven Industries funded this study. TAB and KK have patents (granted or pending) for which Raven Industries is the assignee, but none are related to Raven's patents for the RCA system. The authors all have personal aversions to the negative effects of stress.

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Nomenclature

C = combine operator

CI = confidence interval

EDA = electrodermal activity

GC = grain cart operator

RCA = Raven Cart Automation = Raven Industries' automated on-the-go unloading system

XTE = cross-track error

XTE SD = cross-track error standard deviation