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Integrating Wearable Devices in Real-Time Computer Applications of Petrochemical Systems

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***Abstract*—**As notifications become more common through mobile devices, it is important to understand the impact of wearable devices for improved user experience of man-machine interfaces. This study examined the use of a wearable device for a real-time system using a computer simulated petrochemical system. The key research question was to determine how using information provided by the wearable device can improve human performance through measures of situational awareness and decision making. Results indicate that there was a reduction in response time when using the watch and there was no difference in situational awareness. Perception of using the watch was positive, with 83% of users finding value in using the watch and receiving haptic feedback.

***Keywords*—**Computer applications, haptic feedback, petrochemical systems, situational awareness, wearable technology.

I. INTRODUCTION

As technology continues to evolve, we see the application of dynamic computer systems in industries where safety is paramount, such as healthcare settings, petrochemical plant operations, and the United States Air Force to name a few. These systems tend to be complex in nature and commonly contain an overwhelming amount of sensory input to be interpreted and acted upon by the user. Improving human performance is key to improving safety and man machine interactions in these environments. Human performance hinges on the constructs of situation awareness (SA) and decision making (DM) [1]. SA refers to the level of understanding one has about their environment and increased SA is often correlated with improved human performance, [2]. Endsley's "model of situational awareness in dynamic decision making," suggests that DM is the output of SA [1]. According to Endsley, the way in which humans frame problems impacts the decisions they make to solve those problems. One example of a demanding environment, in which users face challenging dynamic systems, is the petrochemical plant control room.

Operators play a vital role in the overall safety of plant operations. Operator responsibilities include managing elaborate alarm systems and monitoring numerous complex displays. Operators are expected to have strong mental models of existing control systems and exceptionally fast response times to act on alarms and maintain safe operations. Making mistakes in this environment can lead to catastrophic results. The 1994 fires at the Texaco refinery in the United Kingdom burned for two days before they could safely be extinguished. Another example is BP Texas City Refinery (now Marathon Galveston bay) fire/explosion in 2005 that killed 15 people. The UK Health and Safety Executive [3] gives a detailed account of the hydrocarbon fires that broke out that day. Operator error and poorly designed alert management systems directly contributed to these extremely dangerous and costly explosions, with Alarm floods, a commonly cause of this type of operator error [3]. When an alarm flood occurs, alarms come in faster than the operator can respond to them, sometimes more than 55 per minute. Operators end up being less effective in DM when alarm floods occur [4]. Some research has been conducted to explore the nature of such displays and their effect on SA in an attempt to improve conditions for operators. Ikuma et al. attempted to create a guide for assessing petrochemical plant control room interfaces [2]. In the experiment, eye movement, subjective workload, and SA were used to evaluate control room operator performance in terms of speed and accuracy of response times. Two different virtual plant displays, one suboptimal and one optimal, were used in a between-subjects experiment and workload within subjects was tested at easy, medium, and difficult levels. Subjective Workload Assessment Technique (SWAT) and NASA-TLX were used to assess mental workload and the Situational Awareness Global Assessment Technique (SAGAT) was used to assess SA in participants. Results showed that there was a significant interaction between mental workload and type of interface used and that SA scores were sensitive to this interaction. In another experiment, Satuf et al. designed an interface for control room operators that would display the most critical alerts and prioritize them according to acceptable response times [4]. This interface also included access to graphical displays for information about alarm trends. SAGAT and Situational Awareness Rating Technique (SART) were used to assess SA in users. Results showed that SA improved in participants who used the new display versus participants who used the traditional alert summary. Studies like these provide evidence that improving SA in this domain is achievable. However, little research has been done to explore new ways of presenting existing information such as through the use of wearable devices. Even less research has been carried out to examine the potential benefits that wearable devices could provide in terms of improving SA through unique modalities

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such as haptic feedback.

We believe that wearable devices have the potential to improve SA in many real-time computer application systems and the control room operator is just one example. Smart watches contain hands-free capabilities, provide mobility to the user, and they possess a unique modality for capturing a user's attention when other sensory channels may be over stimulated. The literature overview in the next section provides evidence to support the idea that the use of vibrotactile stimulation in conjunction with wearable devices can improve human performance.

II. BACKGROUND

Previous studies support the idea that vibrotactile stimulation may have the potential to improve human performance, particularly in high cognitive workload environments and where other modalities are saturated [5]. The potential for reducing attentional bottlenecks and reducing reaction time when managing complex information systems has also been demonstrated [2], [4], [5]. This kind of technology could complement existing alarm management systems by utilizing a multimodal method for presentation and prioritization of information. Wolf and Kuber developed and tested a head-mounted tactile device aimed at providing additional information to users [6]. Specifically, the researchers investigated the ability of human subjects to discriminate between tactile stimuli presented on a head-mounted tactile display, and the effect that the tactile display had on situational awareness, across a range of tasks with varying cognitive workload. SAGAT scores were used to quantify SA in participants. Results showed that tactile displays improved performance, particularly in perception and prediction [6]. Haas and Van Erp considered the effect of vibrotactile displays on human cognitive performance [7]. They reviewed work in the field and collated findings from several studies. Specifically, they considered multimodal displays in the context of risk communication and safety. In this research, they note that, warning systems are rarely designed with inherent multimodal redundancy [7]. Their review highlights the similarities between the auditory and tactile modalities and their effective uses, limitations, and similarities. Specifically, both modalities exploit multiple resource theory and can effectively deliver information when visual channels are saturated. Another meta-analysis, conducted by Prewett et al. looked at the potential for vibrotactile feedback to augment visual displays across a range of applications [8]. The purpose of the study was to investigate the impact on human effectiveness, rather than situational awareness. Results from this meta-analysis indicated that alert and navigation tasks gave the strongest observed effect [8]. This suggests that a wearable vibrotactile device could be well suited to providing alerts and alarms, which is a key aspect of their potential use in aiding situational awareness and DM. These papers support the argument that a vibrotactile display has the potential to improve human performance in high workload environments, especially where existing visual and auditory channels are saturated or otherwise obscured. Lee and Starner conducted an investigation into the design of a wrist worn system specifically for providing alerts [9]. They evaluated the potential for reducing workload and providing alerts without the need for additional visual interrogation of a display. The study looked at the impact of tactile information on attention to other non-tactile information modalities and the ability of users to interpret tactile displays in the presence of attentional bottlenecks. Lee and Starner [9] and Ziegler et al. [10] reached similar conclusions, with Ziegler et al. [10] concluding that smart watches can significantly reduce user workload in a range of scenarios, while Lee and Starner [9] concluded that smart watches are able to provide easily intuitive alert perception. Ziegler et al. also studied the use of smart watches to compliment other interfaces in the field of industrial maintenance, establishing six use case concepts that define how a smart watch may be utilized in this context; Explicit Information Push/Pull, Implicit Information Push/Pull, Guidance, Communication, Monitoring and Control [10]. The study then examines these concepts in more depth and provides scenarios that develop these use cases. Broad guidelines for some elements of the interaction with smart watches were established, notably that; no single interaction should take longer than 5s, swipe actions should use the entire screen, while tap actions should maximize the target area and inputs should be minimized [10]. While these are just one interpretation, they establish some design considerations areas for tactile User Interfaces (UI).

While these studies highlight the potential benefits of wearable vibrotactile technology, there are potential limitations and caveats to the technology that require consideration. Soto-Faraco et al. investigated the congruency effects between auditory and tactile motion [11]. The authors of [11] used the illusion of ventriloquism as an analogy to explain how information presented in one modality can affect perception in another. In this case, the viewer is tricked into believing sound is coming from the ventriloquist's dummy, while the observers' mental model indicates that the sound would be associated with the movement of the mouth. The study concluded that 'motion cues in these two modalities are integrated' [11]. While this conclusion was limited to motion cueing, it demonstrates that there are potential issues with vibrotactile feedback that may reduce human performance if poorly designed. Jones and Sarter's paper details guidelines for designing tactile displays [12]. The study examined the principle coding parameters of tactile displays: frequency, intensity, locus, and duration. The study concludes that frequency and intensity were the least exploitable dimensions, particularly without the need for training. Despite these potential limitations, improvements in human performance metrics have been clearly demonstrated and there is also evidence that SA is improved but there has been little research into the potential for tactile and multimodal displays to improve DM. Krausman et al. attempted to address the effect of tactile displays on DM [13]. This report for the Army Research Laboratory (ARL) examined the potential for visual, auditory and tactile displays to improve the DM of platoon leaders in a military context. The study considered decision response times and user preference rankings when evaluating these three modalities. The study concluded that visual alerts have a longer response time and are not as effective as auditory or tactile alerts in visually demanding tasks [13]. While the user preference score was aimed at providing a measure of the improvement in DM, there was no assessment of whether or not better decisions were actually made.

Our research question asks: Can a wearable device increase SA and improve DM in petrochemical plant control room operators through optimal information presentation and haptic feedback? Similar studies have shown that the haptic modality can improve situational awareness and alarm response. Boschloo et al. investigated augmenting UAV control systems with haptic feedback to improve collision avoidance warning with the haptic modality demonstrating potential improvement in certain conditions [14]. Much of the research into the impact of vibrotactile alarms has been conducted with respect to the aviation or automotive industries and the methods are not aimed at improving alarm discrimination and reducing or eliminating the effect of distraction. We hypothesize that the use of haptic feedback will increase SA in high cognitive workload environments and secondly that the use of haptic feedback will lead to improved performance in speed and accuracy in relation to DM in dynamic time-critical environments.

III. MODELLING OF WEARABLE DEVICE FOR COMPUTER APPLICATIONS IN PETROCHEMICAL SYSTEMS

An interactive wearable device was developed using Microsoft's model-view-view-model (MVVM) design paradigm [15]. The MVVM pattern contains three layers for information presentation – model layer, view layer and view model layer. The model layer defines the business logic of the app including the business objects, data validation and data access rules. The view defines the UI of the application and the user operates the model with this layer. The View-Model is "view-agnostic", it serves the function of providing data and methods to interact with the view but it does not control how the view will display the data. In the wearable device, when user clicks on a "Tile" on the "Home" screen, it triggers a command in the "View Model" layer. To ensure a realistic petrochemical simulation, the display interface was built using the DeltaV Distributed Control System Simulator (DCSS), developed by Emerson. DCSS simulates a control room operator's interface for controlling various plant processes. The view model layer gets the system state and the model change events to create the UI change that will be presented on the desktop and watch interface. An example of the DCSS interface is shown in Fig. 1.

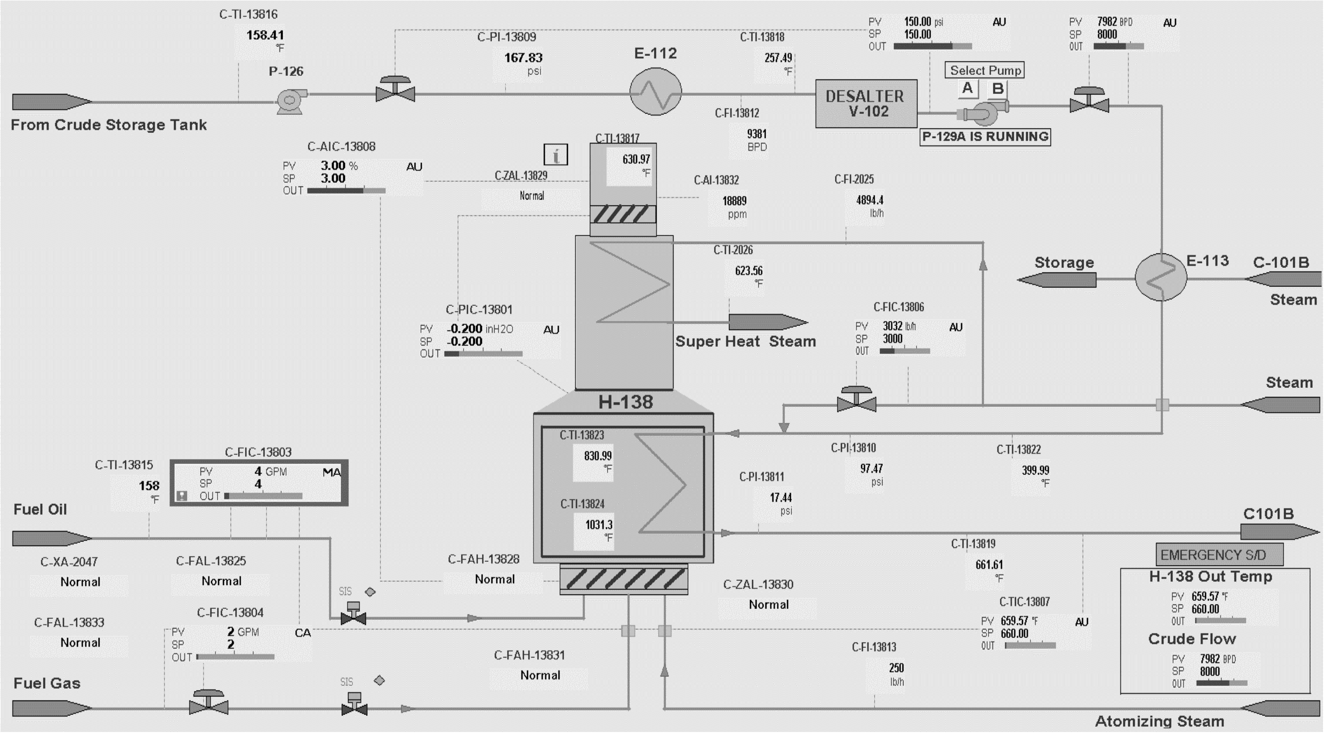
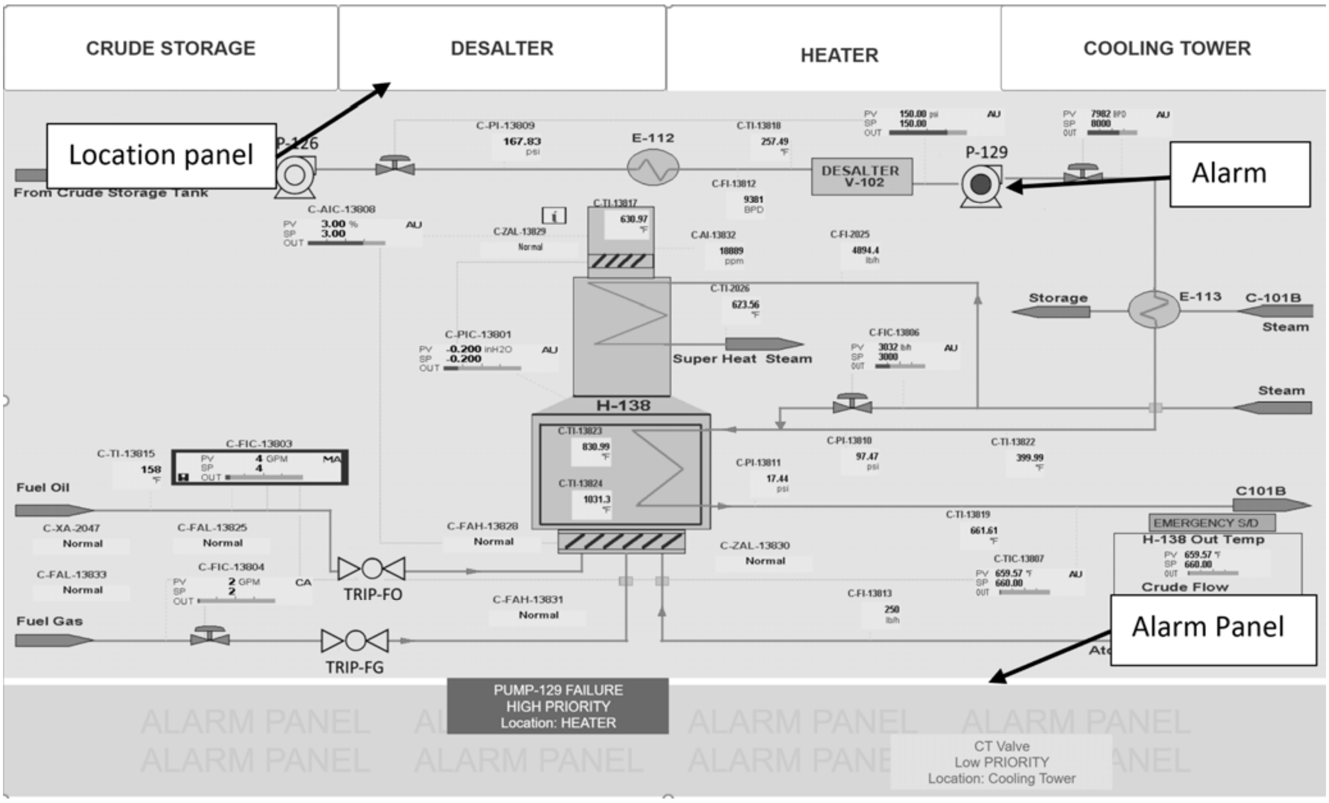


Fig. 1 DCSS interface

The interface for the desktop simulation was developed using Axure RP software that incorporated the DeltaV UI along with interactive elements to display alarm prompts across four plant locations: Crude Storage, Desalter, Heater and Cooling tower. The alarms were displayed in both the location map and on an alarm panel as shown in Fig. 2.

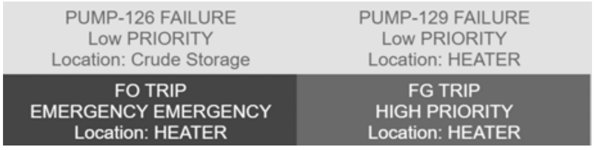


PUMP-129 FAILURE
HIGH PRIORITY
Location: HEATER

CT Valve
Low PRIORITY
Location: Cooling Tower

Fig. 2 Axure UI using DeltaV Simulator UI

Alarms were color coded as yellow for low alarms, red for high alarms, or purple for emergency alarms. In addition to being color coded, alarms contained information about location, time of arrival, and the nature of the problem, see Figs. 3 and 4 for examples of types of visual alarms that participants received on the desktop and smartwatch, respectively. Note that the Watch face only gives an indication of criticality using color to avoid cluttering the small display – the user only knows if there is an alarm and how urgent it is. The user can then confirm the location and additional details using the desktop display.


PUMP-126 FAILURE
Low PRIORITY
Location: Crude Storage

PUMP-129 FAILURE
Low PRIORITY
Location: HEATER

FO TRIP
EMERGENCY EMERGENCY
Location: HEATER

FG TRIP
HIGH PRIORITY
Location: HEATER

Fig. 3 Desktop Alarm Representation

Fig. 4 Smartwatch Alarm Representation

Locations that were available in this experiment included crude storage, heater, desalter, and cooling tower. The variable nature consisted of three elements that commonly need attention while monitoring plant processes. These elements were pumps, valves, and trips. This information about alarm color codes, locations, and nature was obtained through voluntary telephone interviews conducted with Subject Matter Experts (SME) from the Husky Petrochemical Plant in Lima, Ohio. Within the DCS UI, pumps, valves, and trips were outfitted with circular buttons to represent a call to action for participants, see Fig. 5.

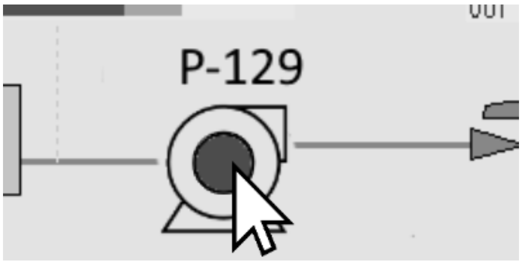


Fig. 5 Call to action button

When alarms came in, the ‘call to action’ buttons would also become color-coded based on the associated alarms criticality. Participants were required to find alarms based on nature and location. Locations that were previously mentioned were available on separate tabs that participants could toggle between. Once an alarm was found, participants could “fix alarms” by clicking on the circular button which would “clear the alarm” and in turn the associated color would disappear.

An Android application was developed using Android

Studio and implemented on an LG Sport 2 smart watch (code implementation is available on request). Haptic feedback about incoming alarms was delivered to participants through the watch. The delivery of feedback was timed in conjunction with the pre-programmed alarms in the interactive prototype. The application was designed to deliver a single 500 ms vibration to the wrist, accompanied by a color-coded square to match the color of the alarm on the DCS UI. Haptic feedback was used to signal to the participant that a new alarm was present on the DCS interface. No physical interaction with the watch was required by participants. All color-coded visuals associated with alarms timed out after 5 seconds. A black screen represented an idle state or the absence of alarms.

IV. METHOD

In order to evaluate the wearable system, a 3x2 within subjects study, approved by the Institutional Review Board, was conducted. The independent variables included scenario difficulty – low, medium, and high; and use of device - with or without the wearable device. Audio distractors were played to simulate the control room environment. Participants (n = 30) consisted of University Engineering Students who volunteered for the study. Upon entering the testing room, participants were asked to read and sign consent forms. A counterbalanced experimental matrix was designed to ensure that results were not influenced by the order in which participants were presented with the various level of difficulties. At the beginning of each new experiment, participants were given verbal instructions by the experimenter to monitor the DCS UI for incoming alarms while completing a distractor task at an adjacent desk. The distractor task consisted of 70 simple math problems and participants completed them with paper and pencil. Participants were instructed to complete the problems to the best of their ability whenever there were no alarms present. A secondary task was included to simulate the complexity of control room operations. The secondary task was a Captcha™ task where participants were asked to identify images belonging to a defined group (e.g., select all pictures with butterflies).

When an alarm was present, participants were instructed to clear all alarms by clicking on the associated pump, valve, or trip before continuing the distractor task. A standard SART Questionnaire [16] was used in this study. The SART was administered after each scenario to capture participant's subjective ratings of their SA. During scenarios in which participants wore the watch, participants were given instructions on their screen to manually start the watch application at the end of a 5 second count down by pressing the "start" button on the watch UI. Participants were required to start the application in this way for each scenario. The Dependent Variables (DVs) of the primary task are: alarm response time, and the results of the SART.

V. RESULTS

Two-way ANOVAs were conducted to assess the variation in both DVs (SA and response time) for both IVs (task difficulty and use of the wearable device). Where significant variation was identified, post-hoc testing was conducted to further examine the significance. Significance was tested using $\alpha = 0.05$.

Situational Awareness: Results from both parametric tests indicated that task difficulty did not have a significant effect on SA ($p = 0.62$) or response time ($p = 0.45$). Kruskal-Wallis results indicated there was no difference in the median SA score ($p = 0.48$) or median response time ($p = 0.44$).

The distributions of both response time and SA scores were tested to ensure that they were normally distributed and had equal variance. The response times were found to be normal ($p = 0.60$) as were the SA scores ($p = 0.83$).

Two methods were used to test for equal variance. First, a visual inspection of the graphical output of the residual for both models was conducted. The residuals for SA and response time indicated equal variance in the data are shown in Fig. 6. Secondly, JMP was used to perform a Welch's test for equal variance (null hypothesis is unequal variance). The SA scores ($p = 0.026$) and the response times ($p < 0.001$) were shown to have equal variance.

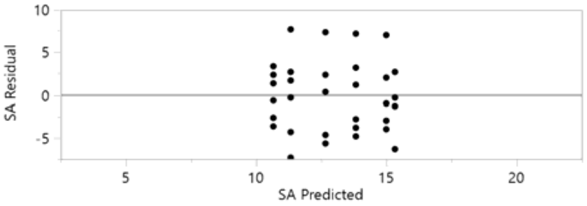


Fig. 6 Residuals from Two-way ANOVA of SA ratings

Results from the Two-way ANOVA showed a significant reduction in response time when the wearable device was present; F (5,30) = 3.96, $p = 0.007$. The R^2 adjusted value for this result was low, with a value of (R^2 adj = 0.029) - implying that approximately 3% of the variation could be explained. There was no significant effect due to the interaction between the two IVs; F (5,30) = 0.04, $p = 0.95$. The most significant two-way ANOVA result was the difference between the users' response time with and without the smart watch. Comparison of the leverage results from these conditions gives a visual indication of the strength of the effect, see Fig. 7.

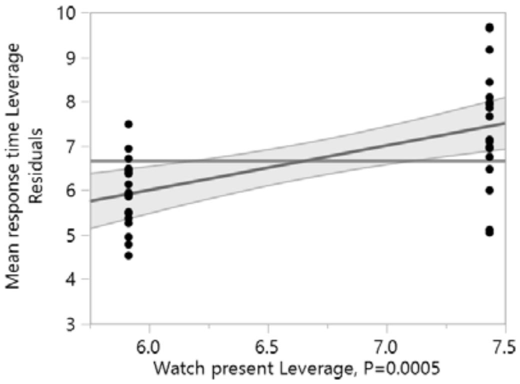


Fig. 7 Two-Way ANOVA Output for Response Time

Response Time: Results from both parametric and non-parametric post-hoc tests indicated that use of the augmented device significantly reduced response time. A One-way ANOVA indicated a significant effect on response time; F (1,34) = 5.42, p = 0.026, effect size = 1.1. The response time to the alarm in seconds was significantly lower with the watch (Mean = 5.9, SD = 0.97) than without (Mean = 7.4, SD = 1.34). The statistical power of this test was 0.9. A Wilcoxon Signed-Rank Test also indicated the median response time in seconds with the watch (Median = 5.85) was significantly lower than without the watch (Median = 7.46); Z (18,0.05) = -3.24, p = 0.02. Note that JMP uses normalized Z-values. The results from these post-hoc tests are shown in Fig. 8.

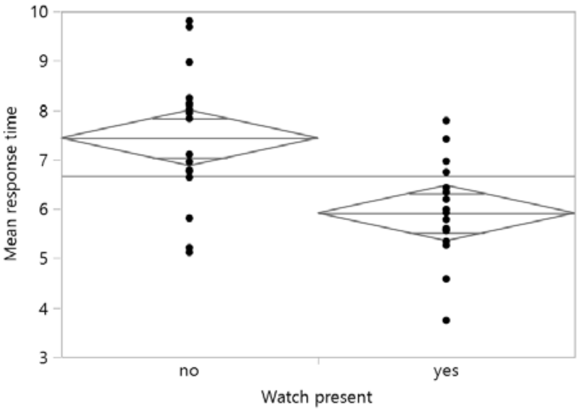


Fig. 8 JMP Post-hoc response time ANOVA plot

Accuracy on Secondary Task: Analysis of the secondary task consisted of one-way ANOVA of the Accuracy. Analysis showed statistically significant improvement in the Accuracy of the participants secondary task performance F (1,30) = 7.89 p = 0.008, see Fig. 9.

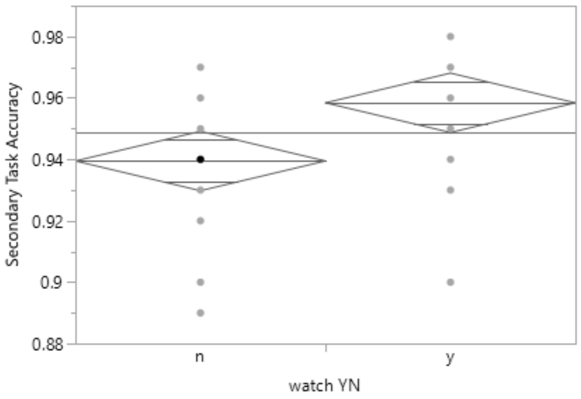


Fig. 9 Secondary Task Accuracy ANOVA with and without watch

Perceptual Data on Ease of Use: As shown in Fig. 10, perceptual data related to user preference and ease of use indicate that users found watch device easy to use and understand. Some 83% of users found value in using watch vs. not using the watch device; 83% of users also found value in haptic feedback for alarms presented on watch interface, while 97% of users found alerts easy to understand on watch interface. Only 20% of the users found the alarm presented on the watch interface to be overwhelming.

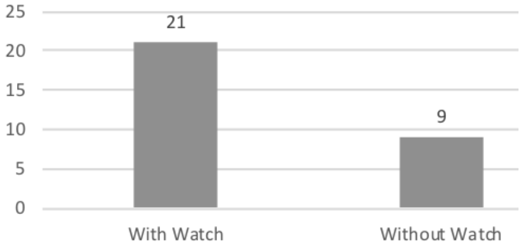


Fig. 10 User device preference

VI. DISCUSSION AND CONCLUSION

The study was designed to investigate the impact of haptic feedback from a wearable device for effective man-machine interface to improve human performance in a real-time computer application such as petrochemical distributed control system. Based on the results, we found that using a watch as a wearable device improved the response time which leads us to believe that using wearable device to inform system changes can be a good mechanism for providing time critical feedback. There was no statistically significant difference between SART scores of participants with or without the use of the haptic alarms, this indicates that SA is not reduced by introducing wearable devices for alarm notification.

Analysis of the secondary task performance showed a statistically significant improvement in accuracy. This shows that as operators use multiple screens and focus their attention to take care of multiple tasks, they will be able to divide their attention effectively to the other tasks while using a feedback mechanism (such as a watch) that does not require them to constantly monitor the primary task.

Previous studies have shown that haptic feedback has potential to improve human performance, in high workload, time critical environments, demonstrating a reduction in attentional bottlenecks and reaction time [7], [10], [11], [13]. The smartwatch used here presents a multi-modal method for presentation and prioritization of information in the petrochemical plant control room. This study contributes to the area of wearable devices in complex systems and understands the use of such modern everyday technologies for seamless interaction in complex systems. Introducing multi-modal feedback using a wearable device can help improve performance while not detrimentally impacting situational awareness. The user satisfaction of using the device was high and the alerts presented on the watch face were easy to understand. As wearable devices become ubiquitous it is important to channelize and integrate them in a meaningful manner to aid human DM in complex computer applications.

While the simulator was designed to be a more deterministic and controllable version of the DeltaV simulator to have repeatability of the experiment, future studies should focus on including dynamic loops to study other aspects of performance such as task load and utilizing a more sensitive measure of SA. Future work could also focus on validating the study with control room operators.

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