Workload Response to Soft Controls Presented on Two Interfaces

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ABSTRACT

Most operational Nuclear Power Plants (NPP) in the United States are primarily outfitted with physical (analog) Instruments and Controls (I&C). However, as parts wear out in legacy plants, these I&Cs are being replaced by digital interfaces. Furthermore, new plants are being proposed and built domestically and throughout the world that are composed primarily of soft controls in the main control room. To that end, it is important to understand if and how various types of interfaces affect performance. The present effort sought to compare a desktop and touchscreen interface. The Instantaneous Self-Assessment, the NASA-Task Load Index, and electrocardiography were used to assess workload response while performing three main control room task types on each interface. Results have implications for interface selection and assessment of new NPP main control room designs.
Key Words: Interface type, workload, physiological response, soft controls

1 INTRODUCTION

Most operational Nuclear Power Plant (NPP) main control rooms (MCR) in the United States are primarily outfitted with physical, or analog, Instruments and Controls (I&C). This means that levers, switches, and gauges are all physically present for interaction and many pre-date any application of usability principals, e.g. most boiler water reactors use a red light for an energized component (pump or generator), or to indicate an open valve for a flow path; a fully withdrawn control rod is designated by a red light, signifying adding to reactor power, whereas a green light signified a control rod is fully inserted, lowering reactor power. On the other hand, the instruments and controls (I&C) are organized by system and mapped visually on the panels for each system in the plant. This layout style is beneficial for mental mapping of system functionality and safety, as well as supporting communication among crew members. Additionally, the entire crew can apply back-up behaviors easily because each member can see the entire set of operating panels and watch as a crew member checks, responds, or detects changes in plant status. However, the prospect of replacing legacy I&Cs with digital upgrades and new plants coming online throughout the world composed predominately of soft controls has a unique set of unknown challenges and benefits. Soft controls are those that are computerized. The commercial nuclear industry is in a transition from legacy analog plants, built in the 1960s and 1970s and licensed to operate into the 2040s [1], to new digital power plants like the AP1000, coming on line in the next few years [2]. The traditional analog plants utilize a larger interface that spans across the walls of the MCR, while the interface of the AP1000 digital plants comprise desktop monitor displays with a keyboard and a mouse, as well as one large display of the reactor core in the front of the MCR. Changes to I&C interfaces can introduce new or different safety concerns including cybersecurity, staffing requirements, navigation and interactio n tools required, communication protocol between crew members needed to be effective, task typ e composition and order in operating procedures, and other performance safety demands. Of part icular importance is the impact of such interface modernizations within NPP MCRs on the task d emands on the ROs, which can impact performance and error rates. These advancements combin ed with the heightened awareness that NPP incidents occur because of an interaction between the human operator and the complex system illustrate the continued need to incorporate human facto rs principles in regulation guidelines of NPP operations [3].

Findings from multiple studies and reports of various safety incidents highlight the impact of the human-system interface on the level of workload experienced (e.g., [4,5]). As a result, the research into complex human-system interfaces (HSIs) has intensified in the nuclear domain [6]. Interfaces can constitute output devices like visual or auditory displays, and input devices such as the keypad. The amount of information, how it is presented in the displays, as well as the ease of logging commands and responses with the input devices, play a large role in how tasks are performed, which in turn impacts the workload experienced. Interfaces with larger displays generally enable more information to be presented, but they also occupy more space and may require the operator to move around more to view the entire display. On the other hand, some interfaces allow more direct input from the user (e.g., using fingers on a touchscreen), while others utilize translated input devices (e.g., using a mouse or joystick). The study of the workload associated with the NPP MCR tasks should incorporate defining characteristics of the interfaces to determine their effects on workload, which can impact performance on the tasks. As a starting point to address safety concerns associated with soft controls, the present effort sought to identify levels and types of workload associated three common task types used in operating procedures for as performed on two different soft control interfaces. The three common task types were checking, response implementation, and detection. The checking task requires a one-time inspection of an instrument or control to verify that it is in the appropriate state. The response implementation task requires an action to affect the state of the NPP. The detection task requires continuous monitoring of a control parameter for identification of change. It was expected that levels and types of workload associated with each task type would differ depending upon the soft controls interface implemented.

In the present study, a touchscreen interface, which had controls that spanned across eight 27' touchscreen WQHD monitor grid (two high by four wide). Much like that in the traditional plants, this interface required the user to walk around to locate particular I&Cs, and directly manipulated the controls without the use of translator devices such as a mouse. On the other hand, the interface of the AP1000 digital plants was simulated using a desktop interface comprised of two 24" desktop monitor displays with the mouse as the input device. Users of the desktop interface had the controls presented on the monitor displays and manipulated the controls using the mouse. They used the mouse to activate the "zoom" (for a close-up view of the control), "pan" (to view the entire panel), "scroll" (move within the panel) functions, and used the "click-drag-release" function of the mouse to manipulate the controls.

The research questions for the present effort were:

1. What was the workload (WL) levels and types associated with each task type?

Hypothesis: It was expected that WL would be greater for the Detection task type followed by the Response Implementation task with the Checking task as the least demanding due to the vigilance involved and the longer duration of the Detection task relative to the other tasks.

Hypothesis: It was expected that different types of WL would be associated with each task type, such that mental demand, frustration, and other similar scales will be greatest for the Detection task type on account of the protracted duration of this task. As the Detection and Response Implementation tasks require additional action and physical response compared to the Checking task, these tasks are likely to elicit a higher level of workload resulting from the physical demands of the tasks.

2. What were types and levels of workload associated with each interface?
   Hypothesis: It was expected that WL would be higher for the Desktop interface compared to the Touchscreen interface, due to the need for additional zooming, panning and scrolling for the Desktop interface. Combining this with expectations that the Detection task would elicit the highest level of workload among the tasks, the greatest WL is likely to be elicited when performing the Detection task on the Desktop interface.
3. What types of errors were associated with different task types?
   Hypothesis: It was expected that the Detection task type would elicit more errors than the Response Implementation task, and the Response Implementation task will elicit more errors than the Checking task.
4. What types of errors were associated with different interface types?
   Hypothesis: It was expected that more errors would be found with the Desktop interface compared to the Touchscreen interface due to the additional actions (zooming, panning, and scrolling) required.

2 METHOD

2.1 Participants

Participants included undergraduate students from the University of Central Florida. As such, control panels and operating procedures were modified according to [3]. Participants served as a reactor operator and confederates served as a second reactor operator and senior reactor operator. A hundred and fifty-two (85 males, 67 females) participants with ages ranging from 18 to 40 (M = 20.56, SD = 3.45) participants were recruited using an online participant pool. Participants were required to have normal or corrected-to-normal vision (including not being colorblind), and have no prior experience using a NPP simulator or operating a power plant. They were also required to refrain from ingesting nicotine at least two hours prior to the experiment or alcohol and/or sedative medications at least 24 hours prior to the experiment.

2.2 Experimental Design

A 3 (Task type: Checking, Detection, and Response Implementation) × 2 (Interface Type: Desktop and Touchscreen) mixed design was employed in the present experiment. Task type was a within-subjects factor while Interface Type was a between-subjects factor. There were twelve steps in each experimental scenario, grouped by task type (4 Checking steps, 4 Detection steps, and 4 Response Implementation steps). To address asymmetric transfer effects, the task types were partially counterbalanced across individual participant presentation. The task types were only partially counterbalanced to create scenarios because the tasks of Checking and Response Implementation are directly linked such that Checking always occurs before Response Implementation in a real NPP and thus, to maintain external validity, task yoking was observed. Scenarios were randomized and counterbalanced across participants. Similarly, certain steps within each task type occur in a given order due to the physics of an NPP. As a result, to ensure ecological validity, the steps within each task type were the same across participants.

2.3 Independent Variables

The independent variables were task type (i.e., Checking, Detection, and Response Implementation), and interface type (i.e., Desktop interface and Touchscreen interface).

2.3.1 Task Type

Task type consisted of three conditions. The Checking task type required a one-time inspection of an instrument or control to verify that it was in the desired state. Participants were required to locate I&Cs and indicate identification by clicking on the correct control. The Detection task type required participants to correctly locate a control then continuously monitor that control parameter for identification of change. Participants were required to monitor the gauge for five minutes and detect changes in level by clicking on an acknowledge button located at the bottom of the gauge. Twelve random changes per minute occurred, totaling 60 changes per Detection task. The Response Implementation task type required an action to affect the state of the NPP. Similar to the Checking and Detection steps, participants were required to correctly identify a control, then manipulate a switch on that control to the desired state (i.e. open/closed). Each task type consisted of four steps that were executed using three-way communication led by the experimenter acting as the SRO.

2.3.2 Interface Type

Two types of interfaces were examined: The Desktop interface and the Touchscreen interface. Participants were assigned to one of the two groups, corresponding to the two types of interfaces. The first group performed the three tasks on the Desktop interface while the second group were administered the same three tasks on the Touchscreen interface. The facility only permitted one interface to be set up for experimentation at a time, and so after experimentation with the Desktop interface was completed, the facility was reconfigured and set up for experimentation with the Touchscreen interface. As interface type was a between-subjects factor (i.e., different participants for each group), there was no threat of any carry-over effect, and thus counterbalancing was not required. Instead, it was more important to establish group equivalence to ensure that any differences found between the groups could be attributed to interface type and not be due to initial differences between the groups. Examination of the group demographics (e.g., gender, age, college major) did not reveal any indication that the groups were not equivalent (p >0.05 for all[1]).

The interfaces inadvertently affected how the tasks were performed because in all three tasks, users had to first locate the control, and interface differences in how the controls are organized over the displays and accessed are likely to influence the time taken to find a specific control. The Desktop interface required the participant to scroll and use a zoom feature to access a close-up view of the controls. Since participants were interacting with a desktop configuration, they were seated for the duration of the experiment. The Touchscreen interface was able to display the instrumentation and control panel in its entirety (i.e., removing the need for scrolling and zooming), but the large interface required participants to stand and move laterally in order to visually scan and interact with the interface. Locating and checking the status of the controls were the main requirements of the Checking task.

The Detection task required users to click on the control (i.e., gauge) each time they detected a change. For the Desktop interface, this entails moving the mouse to click on an area on the

[1] For Age, $t(123.4) = -1.636$, $p = 0.104$, for Gender, $t(151) = -0.233$, $p = 0.816$, for Major, $\chi^2(5) = 10.339$, $p=0.066$. These results indicated that the two groups did not differ in terms of the age, gender and distribution of majors.

control to register detection, but for the Touchscreen interface, uses merely had to touch the area with their finger. Errors are committed when users click on the area next to the control, i.e., the background, instead of the control.

For the Response Implementation task, users were required to manipulate controls to implement an instruction. With the Desktop interface, users had to click the edge of the control "handle", drag it to position and release the mouse button, whereas with the Touchscreen interface, they "touched, dragged, and released their finger" to manipulate the control. These differences may affect the ease to which controls are manipulated, which would be reflected in the number of unsuccessful manipulations or number of repeated attempts.

2.4 Dependent Variables

2.4.1 NASA-Task Load Index (NASA-TLX)

The TLX [7, 8] multi-dimensional questionnaire was used to assess each participant's perceived workload. Subscales included mental demand, physical demand, temporal demand, effort, frustration, and performance. The TLX uses a 100-point sliding scale to rate each subscale. The average score of the six subscales provided a separate measure of global workload. Participants received a copy of the questionnaire with subscale definitions and completed the TLX at the end of each task type, throughout the scenario.

2.4.2 Instantaneous Self-Assessment (ISA)

The ISA [9, 10] was used to measure immediate subjective workload on a five-point Likert scale assessed during the performance of a task [11]. Participants received a copy of the measure with definitions and completed the ISA halfway through each task type using a customized computer program that automatically activated an audio prompt containing the questionnaire. The audio prompt contained the phrase, "please rate your workload," signaling participants to respond by writing down their rating on a sheet of paper.

2.4.3 Electrocardiogram (ECG)

The Advanced Brain Monitoring System B-Alert X10 system was used to monitor the ECG, sampling at 256 Hz. Single-lead electrodes were placed on the center of the right clavicle and one on the lowest left rib. Heart Rate (HR) was computed using peak cardiac activity to measure the interval from each beat per second. The "So and Chan" QRS detection method was used to calculate IBI and HRV [12]. This approach maximizes the amplitude of the R-wave [13].

2.5 Procedures

Participants were provided with a copy of the informed consent, followed by the Ishihara color-blindness test. Participants were informed that another participant (the confederate) who had been trained in a previous session would return for the experimental session at about the time he/she would complete the training. Participants were then trained for two hours using a PowerPoint presentation and the adapted simulator, on either the Desktop or Touchscreen interface. The presentation provided an introduction to the procedures and protocols for participating in a NPP simulation for experimental research. Participants were trained to use three-way communication to clearly relay critical information, navigate within the adapted simulator to locate and read status indicators, respond appropriately to a simulated NPP system warning by following procedures, and complete questionnaires. Each aspect was trained separately and then a practice session combined all components. Proficiency tests were given after each portion, requiring a minimum score of 80% to continue to the experimental scenario. After training, participants were given a five-minute break at which point the confederate arrived for the experimental session. The physiological sensors were connected and a five-minute resting baseline was taken before proceeding with the first task type of the experimental scenario. The steps within the task type were carried-out implementing three-way communication protocol initiated by the experimenter acting as the SRO. The ISA rating was prompted halfway through the condition and the TLX was administered after each task condition block. The same process was followed for the next two task type conditions. The experimental session finished by disconnecting the physiological sensors. Experimental sessions were two hours in duration.

3 RESULTS

3.1 NASA-TLX

A 3 (Task type: Checking, Detection, and Response Implementation) × 6 (Subscale: Mental Demand, Temporal Demand, Physical Demand, Effort, Performance, and Frustration) × 2 (Interface type: Desktop and Touchscreen) mixed ANOVA was conducted. Task type and subscale were the repeated-measures factors, and the interface type was a between-subjects variable. The ANOVA was used to determine if there was a significant workload difference between task types, interface types, and if there were overall differences in the ratings across the subscales. The analyses would also reveal if task type effects differed for the two types of interfaces, and if different combinations of task and interfaces elicited different patterns of workload response, as tapped by the NASA-TLX subscales.

A significant main effect was found for task type, $F(2, 296) = 9.663$, $p < .000$, $\eta^2 = .061$, such that, in general, participants experienced greater workload during the Detection task type (M = 38.759) compared to the Checking (M = 34.302) and Response Implementation (M = 34.035) task types. In addition, a significant main effect was found for the sub-scales of the NASA-TLX, $F(3.067, 453.945) = 50.885$, $p < .000$, $\eta^2 = .256$, such that overall, participant reported higher ratings on the Performance (M = 47.152) and Mental Demand (M = 42.836) subscales compared to the other subscales (Figure 1).

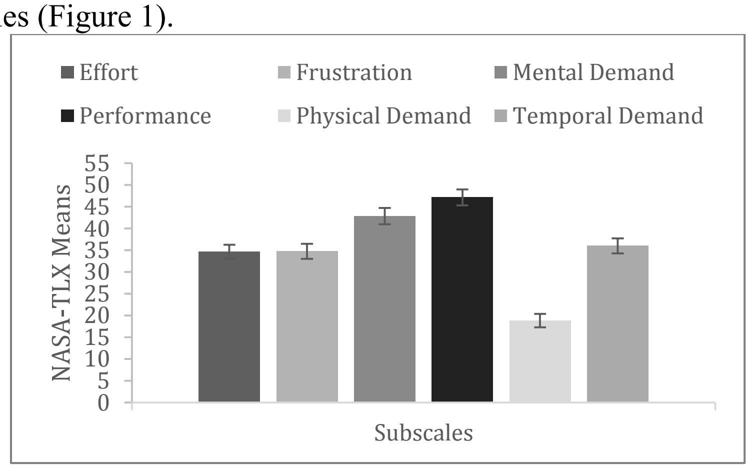


Figure 1: NASA-TLX scores by subscale (error bars denote standard errors)

Examining the effects of task on the different subscales, results showed a significant interaction effect between the task types and sub-scales on the NASA-TLX, $F(6.705, 992.358) = 19.497$, $p < .000$, $\eta^2 = .116$. Not only did the Detection task induce the highest amount of workload overall, the increase was especially marked for Frustration workload (Figure 2).

Furthermore, a significant main effect for interface type was found, $F(1, 148) = 15.556$, $p < .000$, $\eta^2 = .095$, such that workload ratings were generally higher for the Desktop interface (M = 40.464) compared to Touchscreen interface (M = 30.934) groups. However, this increase in workload in the Desktop interface group was much greater for the Performance and Effort subscales, as reflected in the significant interaction effect between the sub-scales on the NASA-TLX and interface types, $F(3.067, 453.945) = 21.302$, $p < .000$, $\eta^2 = .126$ (Figure 2). There were no significant findings for the interaction between task type, sub-scale, and interface type.

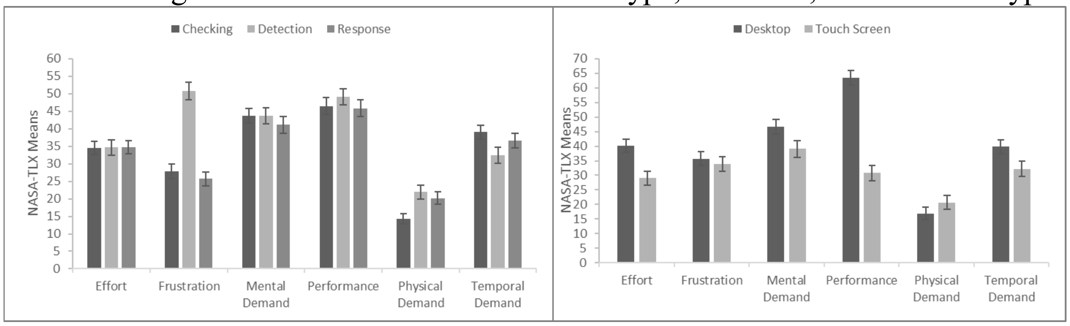


Figure 2: NASA-TLX scores by task type and subscale, and by interface type and subscale (error bars denote standard errors)

3.2 ISA

A 3 (Task Type: Checking, Detection, and Response Implementation**)** × 2 (Interface type: Desktop and Touchscreen) mixed ANOVA was conducted. The ANOVA was used to determine if task type and interface type have significant effects on online-subjective workload (i.e., reported as the task were being performed), and to determine if the pattern of workload differences found across the tasks differed between interface types. A significant main effect was found for task type, $F(1.835, 271.627) = 6.149$, $p = .002$, $\eta 2 = .040$, such that, regardless of interface type, participants gave higher ratings for the Checking task type ($M = 2.400$) compared to the Detection ($M = 2.174$) and Response Implementation ($M = 2.185$) task types. There were no significant differences between the two interface groups in their ISA ratings. The two groups also did not differ on how their ISA ratings differed across the tasks.

3.3 Electrocardiogram (ECG)

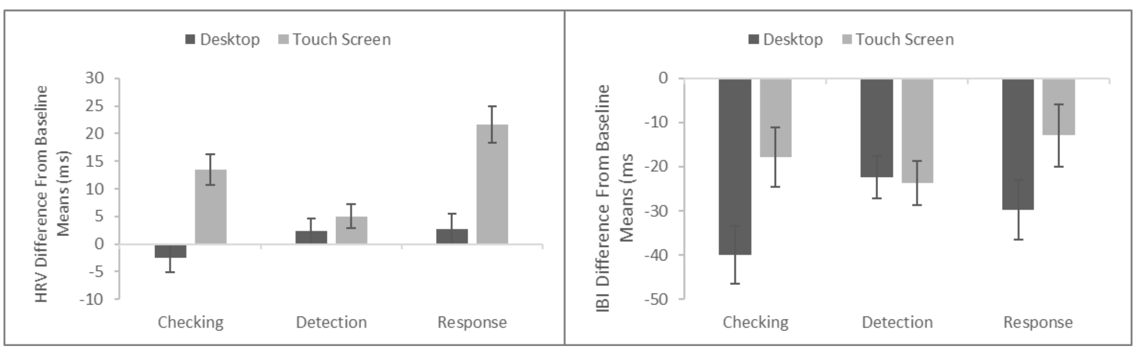
A 3 (Task type: Checking, Detection, and Response Implementation) × 2 (Interface type: Desktop and Touchscreen) mixed ANOVAs were conducted to determine if the different task types and interfaces affected HR, HRV, and IBI. These analyses also assessed the interactive effects between the task types and interface types which would reveal if any differences found across task types were similar for the Desktop and Touchscreen groups. Task type was a repeated-measures variable and interface type was a between-subjects variable.

For HR, a significant main effect was found for task type, $F(1.808, 256.735) = 7.585$, $p = .001$, $\eta^2 = .051$, such that the Checking task ($M = 1.290$) resulted in significantly greater increases in HR from baseline compared to the Response Implementation ($M = -1.850$) task type. A significant main effect was found for interface type, $F(1,142) = 8.833$, $p = .003$, $\eta^2 = .059$, such that participants that used the Desktop interface ($M = 1.846$) showed greater increases in HR from baseline compared to participants that used the Touchscreen interface ($M = -2.378$).

For HRV, a significant main effect was found for task type, $F(1.789, 254.087) = 13.793$, $p < .000$, $\eta^2 = .089$, such that the Response Implementation task ($M = 12.205$) resulted in significantly greater increases from baseline compared to the Checking ($M = 5.457$) and Detection ($M = 3.651$) task types. A significant main effect was also found for interface type, $F(1,142) = 14.550$, $p < .000$, $\eta^2 = .093$, such that participants that used the Touchscreen interface ($M = 13.370$) displayed greater increases in HRV from baseline compared to participants that used the Desktop interface (*M* = 0.838). There was a significant interaction effect between task type and interface type, $F(1.789, 254.087) = 12.484$, $p < .000$, $\eta^2 = .081$, in which the largest differences between the interface groups were found for the Checking and Response Implementation task (Figure 3).

For IBI, a significant main effect was found for task type, $F(2,284) = 3.642$, $p = .027$, $\eta^2 = .025$, such that the Checking task (*M* = -28.959) resulted in significantly greater decreases in IBI from baseline compared to the Response Implementation (*M* = -21.390) task. Also, a significant interaction effect between task type and interface type was found, $F(2,284) = 8.672$, $p < .000$, $\eta^2 = .058$, in which the largest differences between the two interface groups were observed during the Checking and Response Implementation task (Figure 3).

Figure 3: ECG IBI difference from baseline means by task type and interface type and by task type and interface type



4 DISCUSSION

4.1 NASA-TLX

Compared to the Checking and Response Implementation tasks, the Detection task elicited the greatest level of Global workload. This was largely due to the high level of Frustration experienced during the Detection task. The Detection task was essentially a vigilance task where participants had to monitor a gauge for changes for five minutes and click on the "acknowledge" button whenever they detected a change in level. There were 60 changes that occurred randomly throughout the five minutes. As the participants performed all four Detection tasks in succession, they essentially monitored four different gauges continuously for twenty minutes, and had to detect 240 level changes in the gauges. In contrast, the Checking and Response Implementation tasks did not involve vigilance and were much shorter in duration, and so did not elicit as much frustration. The high frustration experienced during the Detection task concurred with similar past findings of elevated frustration during vigilance tasks [13].

The Desktop interface elicited higher workload overall compared to the Touchscreen interface, and the differences between interface groups were most marked for Effort and Performance workload. Workload due to Effort was lower while perceived Performance was higher in the Touchscreen group relative to the Desktop group. The Touchscreen interface did not require as much effort to use, and those who used it tended to rate their performance higher than those who used the Desktop interface.

4.2 ISA

Unlike the results from the NASA-TLX, the workload assessed by the ISA showed that the highest level of workload was experienced in the Checking task. This could be because the aspect of workload tapped by the ISA pertained more to the pace of the task (i.e., participants were instructed that a rating of 2 represented that they felt relaxed and that they had more than enough time for the task, and a rating of 3 represented that they felt like the task progressed at a comfortable busy pace). This corroborates with the higher mean rating on the NASA-TLX's Temporal Demand during the Checking task compared to the other two tasks.

4.3 ECG

Compared to the other tasks, the Checking task elicited greater changes in HR and smaller changes in HRV and IBI from baseline. Previous research has shown that increased HR, decreased HRV, and decreased IBI are linked to increases in workload [14]. These findings corroborate with the NASA-TLX temporal demand and ISA findings in that the higher level of workload induced by the Checking task related to the quicker pace of the Checking task compared to the other tasks.

The Touchscreen interface group seemed to experience lower workload as indicated by their lower HR and higher HRV change from baseline scores relative to the Desktop interface group. This difference was most apparent during the Checking and Response Implementation tasks which showed that the Touchscreen group had higher HRV and IBI. These results concur with findings with the NASA-TLX global workload that also indicated that lower workload was associated with the Touchscreen interface group.

5 CONCLUSIONS

The purpose for the present research effort was to systematically measure workload data associated with the performance of critical tasks in NPP MCR while utilizing a touchscreen or desktop interface of soft controls. The touchscreen results were compared to a desktop results to assess workload when performing critical tasks in an NPP MCR. Both interfaces displayed similar trends in terms of subjective workload and objective workload associated with the three NPP MCR task types. As demonstrated in the desktop interface condition, the detection task was found to result in the highest levels of workload compared to the checking and response implementation task types. Results from the desktop demonstrated that the workload differences between the two tasks were somewhat negligible. However, in the touchscreen condition, several subtle workload differences were found between the checking and response implementation task types as indicated by the ISA and ECG measures. Closer examination of the results highlighted differences in certain task characteristics. The checking task had higher temporal demand due to the rate in which the task was completed, and the response implementation task was able to be performed more effectively due to the location of the controls. This research effort provides clear indication that despite the quicker pace of the checking task and the added requirement of having to manipulate the valves in the response implementation task, the workload was still highest in the detection task which was longer in duration and required participants to be vigilant.

Results on the effects of interface types yielded slightly contradictory results on the surface. Although some subjective measures (e.g., NASA-TLX) indicated that the touchscreen interface was associated with lower overall workload and did not place as much demand on short term memory and certain spatial processes as the desktop interface did, the touchscreen interface induced more physiological activity in the detection task. It is likely that the touchscreen interface, in requiring participants to move around and use their fingers to directly manipulate controls instead of relying on a translated input through a mouse, involved the participants more than the desktop interface. By enabling all the controls to be visible, the touchscreen interface also reduced the demand on short-term memory and selected spatial processing. However, the buttons on the touchscreen interface were also more difficult to reach, especially when they occurred below the shoulder level of the participant. In addition, unlike the desktop interface, participants using the touchscreen interface would only get feedback about the accuracy of their touch after they had performed the action. Participants using the desktop interface could ensure that their mouse cursor was positioned correctly over the button prior to clicking it.

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