Back to Tangibility: A Post-WIMP Perspective on Control Room Design

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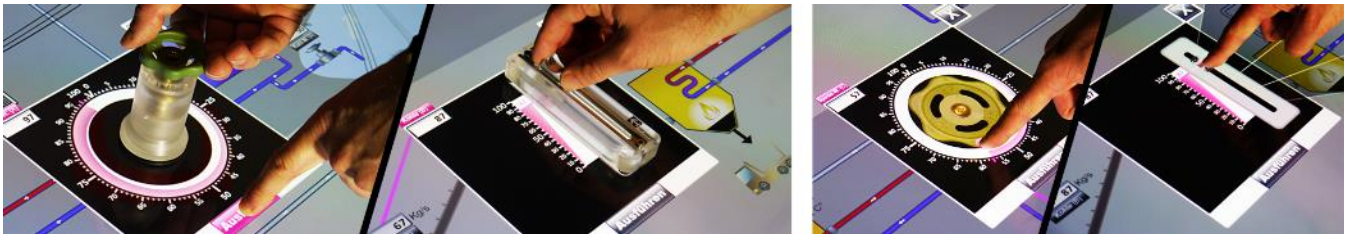

Figure 1. Adjustment of numerical process variables via tangible-object manipulation (left) and direct-touch manipulation (right).

ABSTRACT

In today's digital control rooms, desktop computers represent the most common interface for process control. Compared to their predecessors – manual control actuators – desktop computers enable quick and effective process intervention but they lack in process-related interaction qualities such as haptic feedback and the involvement of motor skills. Thus, design trade-offs have to be made to combine the strengths of both paradigms: today's processing power with the interaction qualities of former control room interfaces. In this paper related interaction concepts are presented and evaluated. In a control room scenario, participants were tasked with adjusting numerical values – so-called process variables – under two traditional conditions (mouse, keyboard) and two post-WIMP conditions (touch, tangible). Task completion time and recall accuracy of the adjusted values were measured. As a result, traditional desktop interaction proved to be faster, whereas control actions could be recalled significantly better using the tangible control elements. We therefore suggest providing both tangible control for process maintenance and traditional desktop interaction in critical situations that require quick intervention.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Interaction styles*

General Terms

Design, Human Factors, Theory.

AVI' 14, May 27 - 29 2014, Como, Italy

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http://dx.doi.org/10.1145/2598153.2598161

Keywords

Control Room, Reality-Based Interaction, Interactive Tabletops, Tangible User Interface, Multi-Touch.

1. CONTROL ROOMS THEN AND NOW

Control rooms are facilities to monitor and control large and complex processes. They can be found in various industrial areas such as power plants, traffic control, or production plants. Process control covers the monitoring of ongoing processes, diagnosis of problem causes, and interventions into ongoing processes [6]. For process maintenance and intervention, the operator has to adjust the physical parameters of the supervised process (e.g. temperature or flow rate), which are termed process variables.

A fundamental change in the relation between operator and process variables has been initiated with the gradual digitization of control rooms. In the era of analog control, operators used to access process variables via manual control actuators such as sliders, buttons, and knobs (Figure 2, left). For operators at the time, the adjustment of process variables was not only perceived explicitly by visual control indicators but also implicitly through motor, haptic, and acoustic feedback that accompanies control actions (e.g. the sound when an actuator clicks into place). As a consequence control actions could be directly associated with the underlying physical process variable. For instance, a rotatory knob typically affects the state of a flow variable. While these attributes may seem insignificant they provided implicit clues regarding a variable's state and eventually helped in establishing an adequate process picture [3].

Figure 2. Evolution of control rooms: then (left) and now (right).

In the course of control room modernization, virtual control elements, which are operated via desktop computers, have replaced their physical predecessors (Figure 2, right). To adjust a process variable, the operator has to navigate to the according process element by scrolling or panning a process flow diagram (Figure 3, background). As soon as the target element has been found, the operator has to select it. Navigation and selection are performed via computer mouse. When a process element has been selected, a dialog window opens on top of the diagram (Figure 3, foreground). Within that window a virtual control element is provided to manipulate the underlying process variable. Value manipulation either happens by metaphor manipulation using a mouse or by typing the reference value into the textbox that holds the actual value using a keyboard.

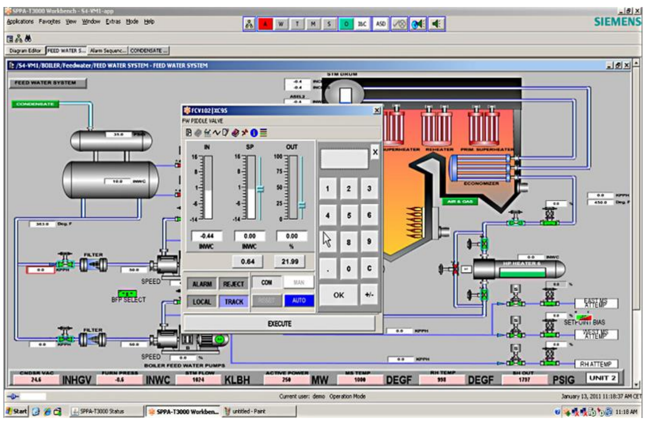

Figure 3. A control system by Siemens AG, showing the process flow diagram (background) and virtual sliders and a textbox to manipulate the selected process variable (front).

While the modernization of control rooms has resulted in an immense increase of processing power, we believe that, in terms of interface design, some important interaction qualities got lost over the years. Salo and Savioja [11] investigated the effects of control room modernization in power plants and confirm this hypothesis in remarking that some of the operators, "who could choose between using either analogue or digital control intentionally carried out operations manually" to maintain process knowledge.

Looking at control room history shows that the interaction paradigms of both eras have individual advantages: the interaction qualities of the analog era and available processing power of the digital era. Thus, in terms of interface design, trade-offs have to be made in order to optimize the balance of both. While desktop interfaces are restricted to indirect interaction with a model world, post-WIMP (Windows-Icons-Menus-Pointer) interfaces open a wide design space: They enable an operator's interaction with the real world – as in the analog era – while taking advantage of the digital processing power.

This paper presents post-WIMP operating concepts for the manipulation of process variables which have been developed with these tradeoff considerations. We first present related work that refers to post-WIMP interaction and the control room domain. We then present related concepts based on interactive surface technology. Finally we report the results of a user study, discuss the applicability of the concepts to the control room domain and reflect on the tradeoff decisions.

2. RELATED WORK

For the design of post-WIMP interfaces in the control room domain Jacob et al.'s work "Reality-Based Interaction - A Framework for Post-WIMP Interfaces" [5] is particularly relevant. The framework is grounded in the observation that post-WIMP interfaces draw strength from users' pre-existing skills and knowledge from their everyday life in the physical world. These abilities are outlined within four themes: Naïve Physics (the common understanding of basic physical principles such as gravity), Body Awareness & Skills, Environment Awareness & Skills, and Social Awareness & Skills. Together, these themes are referred to as "reality" and enable natural interactions. In contrast, unrealistic interface features, such as computer commands, may lead to unnatural interactions and have to be learned in advance. Once they have been learned, they may however provide extra power to the interface. Hence, interface design requires trade-offs between the degree of realism ("Reality") and the power that is provided by digital functionality ("Power"). As a guideline, Jacob et al. [5] suggest making the interface as realistic as possible and that reality should only be compromised for digital (and unnatural) functionality to meet specific design requirements (e.g. such as "versatility" or "ergonomics").

Interactive tabletops represent a popular post-WIMP technology and are attracting increasing interest in the field of control rooms. For instance, Koskinen et al. [8] introduced the "Affordance Table", a multi-touch display for a smart control room concept, and investigated possible touch-gestures for process control. They conclude that the benefits of former manual actuators could probably not be achieved by providing only a model-world approach that is operated by multi-touch interaction. Similarly, Nebe et al. [10] illustrate the potential use of interactive tabletop systems for disaster control management. Their system "useTable" provides multi-touch-, tangible-, and pen-based input.

Depending on the technology interactive tabletops provide the means to control digital information with physical objects, which is why they are also referred to as "hybrid surfaces" [7] or "hybrid environments" [9]. Kirk et al. [7] provide an overview on the two fundamental interaction styles: direct-touch manipulation and tangible-object manipulation. Direct-touch manipulation is based on the manual manipulation of a visual metaphor mimicking real-world principles. Reality may also be deliberately omitted, because the nature of the pixel-based model world allows for according flexibility. In contrast, direct-object manipulation permits the manipulation of digital information by means of physical artifacts and thus provides the qualities of tangible user interfaces following the notion of TUIs according to Ishii and Ullmer [4].

Considering the design space of interactive tabletops, Hancock et al. [1] investigated the advantages and disadvantages of tangible and touch interaction styles. In a 3D object manipulation task and a 2D information visualization exploration task, both interaction styles showed advantages and disadvantages. However both styles drew strength from natural skills from the physical world.

Tuddenham et al. [12] compared the effects of both input styles, tangible-object and direct-touch. The results of a study in which basic manipulation tasks were examined, show that the tangible mode offered more accurate manipulation of digital data. In contrast, they observed an "exit error" problem in the touch mode, which occurred when participants disengaged from a digital object and caused an unintentional movement of the digital representations.

An example of tangible control elements on interactive tabletop systems is presented by Weiss et al. [13] who introduce “Silicon Illuminated Purpose” (SLAP) Widgets. The widget set consists of multipurpose tangibles including a slider element. In an empirical study the physical widgets were tested against respective direct-touch concepts. Physical control elements outperformed the virtual control elements regarding accuracy and overall interaction time. “Madgets” [14], a continuation of the passive SLAP widget set, can actively synchronize with the system’s state and thereby avoid inconsistencies.

Hennecke et al. [2] investigated several adhesion techniques and materials to place tangibles on vertical displays. The techniques were considered under design criteria typical to interactive displays, such as the support of several tracking technologies or reusability of the tangible. As a result, applying vacuum-based adhesion turned out to be the best solution.

3. OPERATING CONCEPTS

The presented post-WIMP concepts for the manipulation of process variables were designed under the tradeoff consideration as suggested by Jacob et al. [5]. In order to investigate the effects of the tradeoff decisions, operating concepts were designed for two input modalities with different power and reality proportions: a tangible-object and a direct-touch concept. As common actuator types we chose one rotatory control element and one slider control element as defined in DIN EN 894-3. Rotatory control actuators are operated via a rotatory handle with continuous actuation. The element allows operations without visual contact, however it does not support visual control because the handle does not provide information about its internal (rotatory) state. Setting the control to its minimum and maximum state is perceivable by a stop. The element is used for flow variables. The slider control enables operation without direct visual contact due to the physical constraints of the guide slot. Setting the maximum and minimum value is accompanied with a perceivable resistance caused by the lower and upper constraints of the guide slot.

All concepts are embedded in a dialog window (Figure 4 and 5), which includes the actual value of the process variable as a numerical value (top left) and a button to confirm the actual value (center, bottom). The visualization of each concept has a passive state (gray, no contact is detected) and an active state (magenta, contact detected). For all concepts of the rotatory element, the min and max value is placed at 12 o’clock position.

3.1 Tangible-Object Operating Concepts

Both element types of the tangible-object concepts (Figure 4 and 5) inherit the handling qualities of the respective model actuators that are described in the DIN document. For both element types an adhesion layer (as suggested in [2]) prevents the tangibles from accidental movement on the surface and preserves the original physical constraints. For both element types level indicator appear seamlessly on the display as soon as the physical element is detected by the tabletop (Figure 4). In terms of design trade-offs (as understood in RBI) the concepts are characterized by a high degree of realism as they inherit the essential operation styles of their model. This also includes the physical constraints at the respective minimum and maximum position of the operation amplitudes. While this limits quick operation (in particular for the rotatory control), it preserves the haptic feedback at the rotation ends (rotatory control) and the translation ends (slider control), making the adjustment of extreme values literally “tangible”.

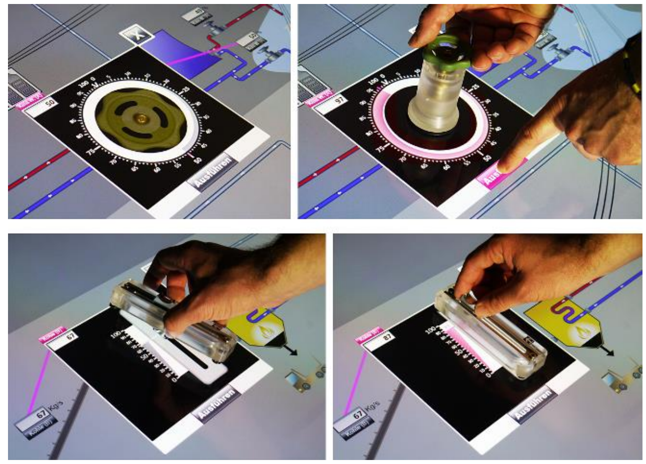

Figure 4. Tangible-object manipulation: the rotatory control (top) and the slider control (bottom) element. Level indicators are in passive mode (left) until the tangible is detected (right).

For the rotatory control concept (Figure 4, top) the digital level indicator appears in a concentric circle around the contact area. The shape of the level indicator corresponds to a bent triangle, which emphasizes the direction code. In the sense of readability the level is aligned to the outside of a white ring, seamless to the numerical value scale. The visualization adjusts to the internal rotation state of the element when placed on the tabletop. For the slider control concept (Figure 4, bottom) the digital level indicator appears alongside on the left of the handle. The state of the variable is emphasized through the shape of a wedge profile.

3.2 Direct-Touch Operating Concepts

The direct-touch concepts mimic the conceptual model regarding their operation mode and their photorealistic rendering. In order to intensify their logic affordances a fingertip-sized, non-photorealistic control knob is placed on the rotation wheel and on the sliding knob image (Figure 5, left). The knob controls the visualization and the current value is adjusted accordingly. Due to the pixel representation interaction in the direct-touch concepts is not limited by the laws of physics. This creates opportunities for less natural, yet powerful operating features which have been traded off for some degree of realism. For instance it is possible to

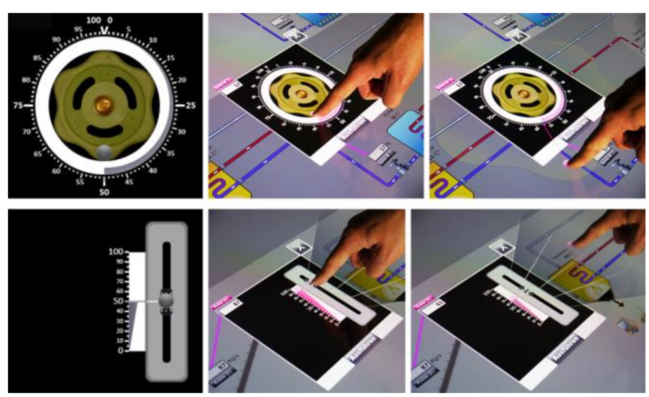

Figure 5. Direct-touch manipulation: the rotatory control (top) and the slider control (bottom) element. Additional affordances are provided through an extra control knob in the shape of fingertip-sized handles (left). The user can perform unnatural yet powerful actions by freely moving this handle.

point at any position on the visualizations whereon the knob moves instantly under the respective touch position. While pointing allows quick value manipulation, it is relatively imprecise. In order to counter this imprecision, element-specific features were added and are described in the following.

In the rotatory control concept it is possible to freely drag and move the control knob, leaving a connection line to the level indicator (Figure 5, top). Consequentially moving the knob beyond its original radius provides slow but precise interaction whereas bringing the knob towards the center of the wheel provides quick yet imprecise interaction. Thus the user has steady control over the speed vs. accuracy tradeoff. As soon as the finger is lifted off, the handle snaps back to the initial radius onto the wheel. To keep the mapping between control point and the photorealistic wheel, an additional, semitransparent wheel appears as soon as the control knob is moved outside the original radius (Figure 5, top right).

Similarly, in the slider control concept the control knob controls the photorealistic handle, the level indicator, and the value adjustment. As soon as the slider control element is touched, a virtual isosceles trapezoid appears on the right hand side of the guide slot (Figure 5, bottom). The user can pull the control knob into the trapezoid (Figure 5, bottom center and right), which scales the distance that has to be passed to cover a specific value interval. Thus, movements near the guide rail are quicker but more imprecise whereas movements near the long right edge are slower due to the scaling factor, but at the same time allow more precision. As with the rotatory control concept the visual metaphor can be touched anywhere whereby the visualization and the numerical value is adjusted instantly.

3.3 Comparison of tradeoff decisions

The described concepts represent alternatives to the current manipulation of process variables. In practice, two common scenarios exist: Either the operator interacts exclusively through the computer mouse (navigation and manipulation of virtual control element) or via mouse and keyboard (navigation via mouse, selection of textbox via mouse and value manipulation by using the keyboard numbers). In order to include the traditional concepts in the consideration of design trade-offs, respective input styles were implemented with the presented visualizations.

In the mouse concepts the visual metaphor can be manipulated similar to the direct-touch condition. Due to the technological characteristics, mouse interaction is more precise. At the same time it provides less feedback in terms of physical qualities such as the activation of motor skills that are associated with the typical operation styles of the element. In the keyboard concept the textbox displaying the current value is selected first. Afterwards the target state of the process variable is entered via the number keys of the keyboard. Value adjustment with the keyboard provides neither tactile nor motor aspects that are associated with the operation of control actuators. On the other hand it allows instant and precise setting of the target value.

Table 1 summarizes these tradeoff decisions in terms of operational power and the physical qualities associated with the operating concepts.

Table 1. Design consideration and assumed effects

	physical qualities	operational power
tangible-object	++ *very high:* instantiation of (real-world) model including its physical operation qualities (tangible feed-back and involvement of motor skills).	- - *very low:* no shortcuts as of perpetuation of physical properties; no added functionality.
direct-touch	+ *high*: direct manipulation of visual metaphor; thus according motor involvement. No physical constraints, though.	- *low:* same as mouse plus opportunity for bimanual operation; however less precise due to technological restrictions.
mouse	- *low:* requires indirect input device, thus motor involvement reflects movement that is associated with the (physical) model only marginally	+ *high:* opportunity to quickly and precisely manipulate metaphor.
keyboard	- - *very low* operating style does not provide association between control action and physical variable.	++ *very high* opportunity to quickly set arbitrary values, e.g. big intervals.

4. EVALUATION

We investigated the presented concepts in terms of two criteria which are particularly important in the control room domain: the time it takes to make value manipulations (task completion time) and how well the performed control actions could be recalled (recall accuracy). Based on our tradeoff decisions and their assumed effects (see Table 1) we hypothesized that (1) task completion time is shorter with traditional input styles due to the provided operational power and that (2) post-WIMP interaction styles provide better recall accuracy due to their physical qualities and the richness of feedback. Hypotheses were tested in a factorial within-subjects design

4.1 Operationalization and design

Independent variables refer to the input conditions and consist of the two factors *input style* (keyboard vs. mouse vs. direct-touch vs. tangible-object) and *element type* (rotatory control vs. slider control). From the two factors 8 input conditions can be generated (Figure 6).

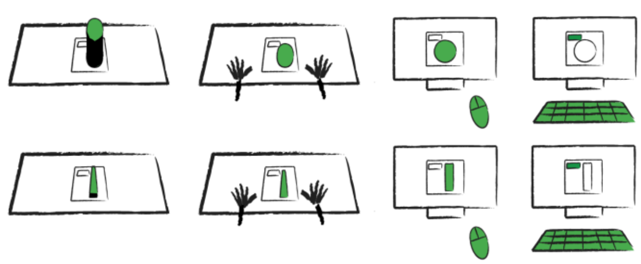

Figure 6. 8 conditions; input style (column): tangible vs. touch vs. mouse vs. keyboard and element type (row): rotatory control v. slider control.

The first dependent variable *task completion time* was operationalized in terms of the time it took participants to adjust a series with given target values. It was measured with the help of interaction logging. The second dependent variable, *recall accuracy*, was defined as the number of control actions, i.e. the manipulation of values, which could be recalled correctly in terms of target values. Recall accuracy was measured by means of a reconstruction task at the end of a manipulation series. In addition, personal concept preferences were gathered by means of a questionnaire consisting of closed-ended and open-ended questions at the end of an input condition.

The study was counterbalanced for *input style*, resulting in 24 different test sequences of conditions. *Element type* was treated as a characteristic feature of *input style* and was thus tested within *input style*. The order of conditions within each test sequence was randomized and set before each test.

4.2 Setting, Tasks, and Procedure

To better understand the effects of the concepts and discuss their applicability for the control room domain, we designed a context-free part (Part A) and a control room task scenario (Part B). In both parts, participants switched between a desktop system and an interactive tabletop, depending on the interaction style (Figure 7).

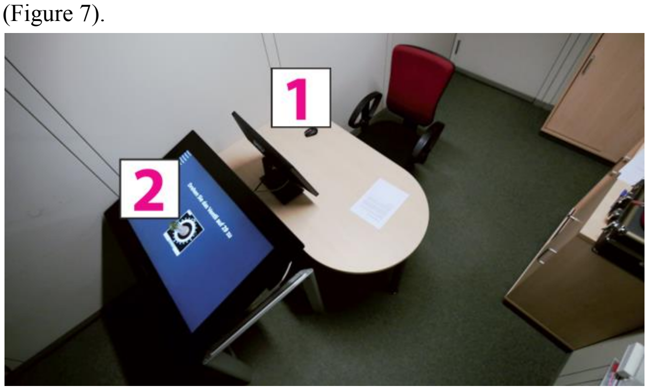

Figure 7. Traditional interaction styles at a desktop system (1) and post-WIMP interaction at a Samsung SUR40 (2); both with a resolution of 1920 x 1080.

At first participants were welcomed and provided a questionnaire on their demographic and technological background. Afterwards they were introduced into the concept behind each condition. Then participants were introduced in Part A and then performed the task of this part. Same procedure was repeated for Part B. After Part B participants were compensated with 12 Euros. Each study took approximately 100 minutes.

In Part A each of the 8 conditions, participants had to adjust a series of 5 numerical values ranging from 0 to 100. Whenever a correct value was confirmed, the next target value appeared. Otherwise feedback was provided in the form of a red glow effect around both the entered value and the target value. After each series a cover appeared on the screen and the participants were asked to reconstruct the series of numbers they had adjusted. All 8 conditions where repeated, since we expected a learning curve.

For Part B we chose the domain of energy production. The process was simplified and mapped on a virtual process flow diagram (Figure 8). Through coal combustion, feed water is heated. The resulting steam drives the turbines that are connected to power generators. In order to maintain the process, cooling water is required. In terms of process variables, the slider control

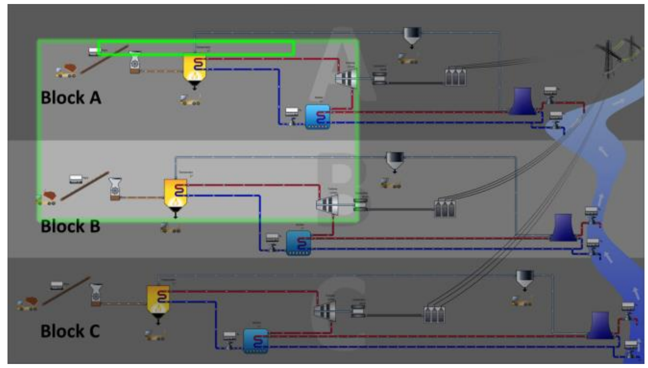

Figure 8. Process flow diagram, off-screen content is shaded. The smaller green rectangle marks the area where task instructions appeared.

was mapped to the conveyor belt that regulates the amount of coal (ranging from 0 to 100 tons/minutes) that runs into the combustion chamber. The rotatory control was mapped to the variables that control water throughput, that is, feed-, cooling-, and sewage water, each ranging from 0% to 100% throughput. All process variables were represented as icons and a corresponding actual value. For interactive process variables, actual values were displayed in a selectable textbox, while those variables, on which the user had no direct access (e.g. the temperature in the combustion chamber) were presented as simple text labels. The virtual process flow diagram spanned double display width and height. The diagram covered three schematically identical energy production processes (Figure 8) which could be navigated by panning the process flow diagram.

Due to the task scenario, in which the proportion of control elements was not balanced (3 flow variables via rotatory element and 1 variable via the slider element), only *input style* was considered. Each of the resulting 4 conditions were introduced by a little story providing background information on the overall process state (e.g. that the coal truck-drivers went on strike, causing several process interventions). Within each condition, participants were exposed to a series of 6 task instructions appearing on the top border of the screen (Figure 8). Each task instruction was formulated as a simple sentence containing the target element (e.g. cooling water in Block B) and the target value (e.g. 80%). Each instruction had to be confirmed in order to unlock the process flow diagram. As soon as the participant found and selected the correct target element the diagram was shaded and navigation was disabled. At the same time a dialog window showing the element visualization appeared. After adjusting the value, participants had to confirm the control action and the next instruction appeared on the upper border of the screen. The proportion of *element type* was balanced across all 6 instructions. After completion of the 6th instruction the screen was again covered and participants started the reconstruction task (Figure 9).

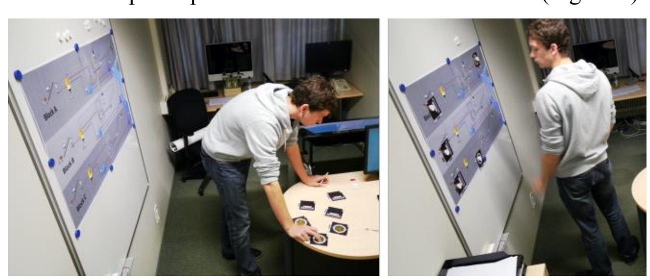

Figure 9. Reconstruction task on a paper-based flow diagram.

5. RESULTS

We recruited 24 participants (9 female, 15 male). The mean age was 25.4 years (SD = 3.1, min = 20 years, max = 36 years). The participants consisted of 19 students, 3 apprentices and 2 employed persons. Five participants were 5 left-handed. Computer experience was indicated with 12.8 years on average (SD = 3.1). On a scale from 1 (“novice”) to 5 (“expert”) computer expertise was indicated with 3.4 on average (SD = 0.6). 18 participants reported prior experiences with touchscreen technologies.

For all statistical tests we used an alpha level of .05. Analyses of task completion time and recall precision were done using parametric methods of analysis and post-hoc pairwise comparisons if normal distribution was given. All post-hoc tests were Bonferroni corrected.

5.1 Part A

No learning effects could be identified between the first 8 series of value manipulations and the repetition (series 9 to 16), only series 9 to 16 were taken into consideration for analysis.

Task Completion Time: Value manipulation was performed fastest in the keyboard/slider condition with a duration of *M* = 20.82 s (*SD* = 8.86 s). The longest manipulation time was measured in the touch/slider condition with a duration of *M* = 51.41 s (*SD* = 15.37 s) (Figure 10). A two-way repeated measures ANOVA revealed a significant main effect for input style ($F(3,69) = 74.74$, p = .000), and a significant main effect for element type ($F(1,23) = 10.57$, p = .004). Interaction between the input style and element type was also significant ($F(3,69) = 7.94$, p = .000).

A one-way repeated measures ANOVA for each element type was performed. Pairwise comparisons in the element type “rotatory control” revealed that manipulation in the keyboard condition (*M* = 21.99 s, *SD* = 9.39 s) were performed faster than in the mouse (*M* = 33.66, *SD* = 7.63 s, p = .000), the touch (*M* = 38.59 s, *SD* = 10.36 s, p = .000), and the tangible (*M* = 40.08 s, *SD* = 10.09 s, p = .000) condition. A significant difference in task completion time could also be revealed between the mouse (*M* = 33.66 s, *SD* = 7.63 s) and the tangible condition (*M* = 40.08 s, *SD* = 10.09 s, p =.000). Pairwise comparisons in the element type “slider control” revealed that manipulation in the keyboard condition (*M* = 20.82 s, *SD* = 8.86 s) was performed faster than in the mouse (*M* = 36.43, *SD* = 10.97 s, p = .000), the touch (*M* = 51.41 s, *SD* = 15.37 s, p = .007), and the tangible condition (*M* = 38.99 s, *SD* = 10.90 s, p = .002). Manipulation via touch (*M* = 51.41 s, *SD* = 15.37 s, p = .007) was also significantly slower than via mouse (*M* = 36.43, *SD* = 10.97 s, p = .000) and tangible (*M* = 38.99 s, *SD* = 10.90 s, p = .007).

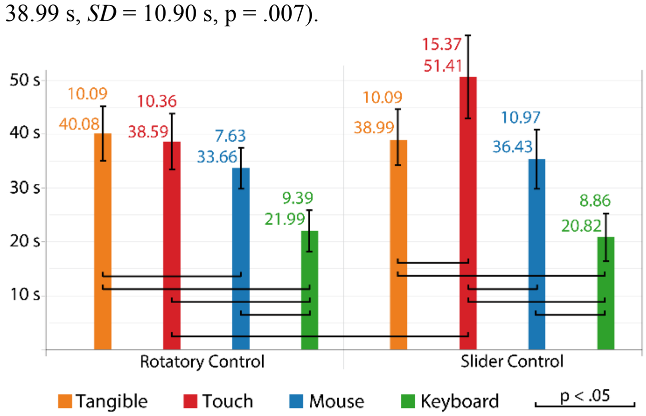

Figure 10. Task completion time in seconds.

Analysis of task completion time of the element type within input style showed that in the touch condition the rotatory control (*M* = 38.59 s, *SD* = 12.77 s) outperformed the slider control (*M* = 52.51 s, *SD* = 11.47 s, p = .001).

Recall Accuracy: Participants were able to reconstruct the most items in the tangible/rotatory condition (*M* = 3.71, *SD* = 1.30) and the fewest in the mouse/slider condition (*M* = 2.67, *SD* = 1.71) (Figure 11). A two-way repeated measures ANOVA revealed no significant main effect for element type ($F(1, 23) = .06$, n. s.) but for input style ($F(3, 69) = 6.44$, p = .001). There was no significant interaction effect, ($F(2.59, 59.73) = 0.05$, n. s.). For input style a pairwise comparison of estimated marginal means showed a significant difference between the number of recalled values in the mouse (*M* = 2.93) and the tangible condition (*M* = 3.68, p = 0.02).

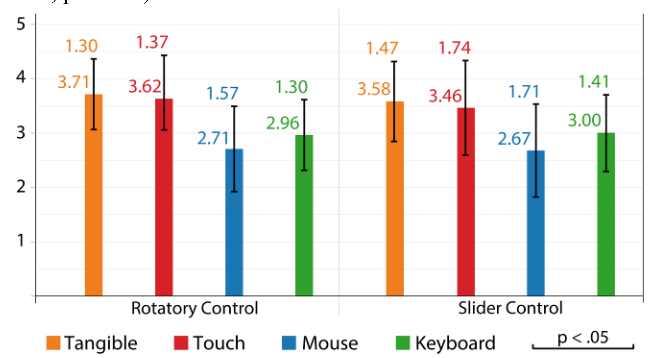

Figure 11. Recall accuracy in number of items. Statistical significance according to estimated marginal means between tangible and mouse condition are not indicated in this figure.

Additional Data showed no significant preferences in the ranking of conditions. In terms of recall strategy, 11 participants indicated that they tried to associate the values they were exposed to with personal, familiar numbers such as birthdays or years of age. 9 participants reported to have mentally repeated the values until the reconstruction task started. 6 reported that they tried to recall the visualization if other strategies failed. From these 6 participants, all assumed that they were more successful in recalling values from the rotatory visualization than from the slider visualization. In general participants criticized the lack of precision for the touch concept of the slider control as values happened to alter when lifting the finger. Participants also criticized the imprecision of the tangible-object concepts (*“The tangible is hard to adjust sometimes.”*), but valued the physical experience that they provide (*“You can actually feel the adjustment of values.”*).

5.2 Part B

In the task scenario input style was considered as the only independent variable. Thus, following results only refer to the individual input styles, but not to the element types.

Task Completion Time took longest in the tangible condition (*M* = 58.80 s, *SD* = 10.73 s) while value manipulation was performed within the smallest time interval in the keyboard condition (*M* = 34.55 s, *SD* = 9.70 s) (Figure 12). A one-way repeated measures ANOVA yielded a significant main effect ($F(3,69) = 36.12$, p = 0.000). A pairwise comparison revealed a significant shorter task completion time in the keyboard condition (*M* = 34.55 s, *SD* = 9.70 s) than in touch condition (*M* = 43.66 s, *SD* = 12.34 s, p = .042) and in the tangible condition (*M* = 58.80 s, *SD* = 10.73 s, p = .000). Task completion time in the tangible condition was lower than in the mouse condition (*M* = 37.86 s, *SD* = 7.23 s) and in the touch condition (*M* = 43.66 s, *SD* = 12.34 s).

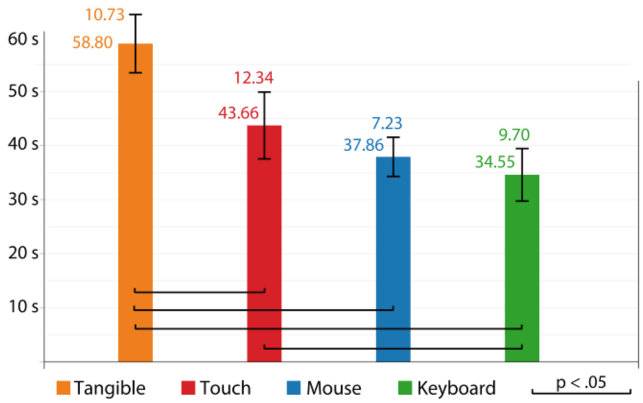

Figure 12. Task completion time in seconds.

Recall Accuracy: participants recalled most values in the tangible condition (*M* = 3.69, *SD* = 1.48) and least in the mouse condition (*M* = 2.94, *SD* = 1.60) (Figure 13). Normal distribution was not given. A Friedman test revealed a significant main effect ($X^2(3) = 9.23$, p = .026). A Wilcoxon signed-rank test yielded a significant higher mean values in the tangible condition (*M* = 3.69) than in the keyboard condition (*M* = 3.15, *Z* = - 2.33, p = .019), in the mouse condition (*M* = 2.94, *Z* = -2.81, p = .005) and in the touch condition (*M* = 3.10, *Z* = -1.97, p = .048).

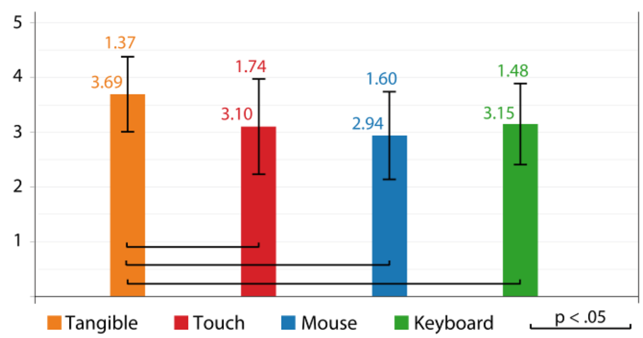

Figure 13. Recall accuracy in number of items.

Additional Data: Wilcoxon signed rank test revealed that the keyboard condition (mean rank = 3.21) was ranked significantly lower than the mouse condition (mean rank = 2.42, Z = -2.486, p = .013), the touch condition (mean rank = 2.42, Z = -2.11, p = .035), and the tangible condition (mean rank = 2.08, Z = -2.3, p = .021). As recall strategy 21 participants reported that the scenario helped them in recalling and assigning the correct values. 7 participants reported that the tangible-object manipulation would help in comprehending control actions. 9 participants remarked that there was an interaction gap in the process flow in the tangible and the keyboard condition as the step from navigation and selection to manipulation required a shift of input styles *("Shifting interaction modalities made it tricky at some points, for example in the keyboard and in the tangible condition"*).

6. DISCUSSION

The results from both parts show that the input style has an effect on both task completion time and recall accuracy. In the following the results of each part are discussed individually.

Part A, Task Completion Time: Value manipulation was performed quickest in the keyboard condition irrespective of the element type. The mean values reflect the expectations from the design trade-offs (Table 1) except for the touch condition with the slider element. For the slider control we assume that participants did not make extensive use of the provided extra operational features, and that the reported exit entry problems caused the participants to readjust the value. These usability issues would need to be addressed twofold: 1) in terms of providing better affordances to make participants make use of precise manipulation mode near the long trapezoid edges, and 2) in terms of generally reassessing the slider concept for the given value range. Comparing the mouse condition – as a traditional input style – with the tangible-object condition shows that there is no significant difference for the slider element. At this point three potential reasons could be identified 1) that the additional operating features in the mouse condition were not used, 2) that the direct-pointing option was not precise enough and required the readjustment of values in some cases, and 3) that bimanual control in the tangible-object condition enabled participants to effectively perform the value manipulation with their dominant hand and at the same time confirmed the value with the other hand.

Part A, Recall Accuracy: There were no interaction effects, thus the factor input style can be considered independently from the factor element type. Comparing the mean values of the post-WIMP concepts with the traditional input styles largely reflects the expectation that manipulating the process variables in post-WIMP conditions lead to a better recall precision. Yet, referring to Table 1, the results show two unexpected effects: First, the recall accuracy was significantly better in the keyboard condition than in the mouse condition. This can be explained by that fact that task completion time was quickest for the keyboard and that participants could better keep the values in their short term memory as they were able to start sooner with the recall test. The reported recall strategies support this assumption as some participants tried to keep the values in short term memory by mentally repeating them. Furthermore, the estimated marginal means showed that recall accuracy was significantly higher in the tangible-object condition than in the mouse condition. This is remarkable, given that in terms of task completion, the mouse condition performed better only for the rotatory control.

Part B, Task Completion Time: Traditional input styles were significantly faster than the post-WIMP styles as hypothesized, except for the mouse condition, which outperformed only the tangible-object condition. Furthermore, referring to Table 1, the keyboard condition performed unexpectedly worse than the mouse condition. Similarly, the tangible-object condition performed significantly worse than the direct-touch condition. Both cases can be explained by the eventuality of the task scenario: Value manipulation in the direct-touch and in the mouse conditions happens fluently in the sense that the typical interaction flow (navigation, selection, manipulation) happens with one input style, whereas in the tangible-object and the keyboard condition, the task scenario requires a change of input style. This is supported by the participants' concerns that this might have cost them extra time.

Part B, Recall Accuracy: Considering the number of process variables that were correctly recalled and placed on the appropriate position of the process flow diagram, the tangible-object condition outperformed all other conditions. While there were no further significant differences among the other elements, the mean value of the keyboard condition was unexpectedly higher than that of the mouse and the direct-touch. Similar to Part A we can assume that this is a side-effect of the low task completion time in the keyboard condition, allowing participants to better keep the values in their short term memories. A general comparison for recall accuracy cannot be made with the first part due to the different reconstruction task. Unlike in Part A, however, participants reported that the task scenario helped them in understanding and reconstructing their performed control actions. In general, the tangible concepts were appreciated, while in contrast to Part A their imprecision did not play a major role.

Finally, we allude to the limitations of this study: *First*, the study was not conducted with control room operators. Thus, results and conclusions referring to the task scenario do not necessarily apply to real-world settings. *Second*, the factor element type was not observed individually in Part B. Possible interaction effects, such as observed in Part A, could therefore not be investigated in the task scenario. *Thirdly*, the aspect of recall accuracy requires further research because it raises the following question: How does a long exposure time of the target value (as in those conditions with a high task completion time) contribute to recall accuracy compared to a short task completion time (as in the keyboard condition) within which participants could better retain the values? In addition, we suggest considering reconstruction tasks designed to assess the effect of long term memory, as it may better reflects typical operator work.

7. CONCLUSION

In this paper we illustrated that – for the manipulation of process variables – the desktop as the common interface lacks process-related interaction qualities such as haptic feedback, physical constraints, and the involvement of motor skills. As a starting point, we proposed the concept of design trade-offs according to the framework "Reality-based Interaction" [5] and presented a direct-touch and a tangible-object concept for both a slider element and a rotatory control element.

In a user study we compared these concepts with traditional desktop interaction in terms of task completion time and recall precision of the participants' performed actions within a task scenario. As hypothesized, traditional manipulation of process variables via the keyboard outperformed the direct-touch and the tangible-object concepts. Manipulation in the mouse condition, however, was not significantly faster than in the direct-touch condition. In terms of recall accuracy, the tangible-object condition outperformed all other conditions and manipulation with the tangibles were perceived most positively as they were reported to enable a better understanding of the performed control actions. Furthermore, participants expressed concerns in the keyboard and the tangible-object condition in which they had to change the input style. To optimize this workflow in the tangible condition, we suggest the following two solutions: First, by using the feature of self-actuation such as described in [14]. This would enable the tangibles to autonomously move to the according position onto the process flow diagram. A second solution could consist in a set of static tangible control elements placed near the display borders. Operators could navigate the process flow diagram on the touch screen with one hand and perform the value manipulation with the other hand. As the tangibles allow blind operation this would also enable operators to keep their focus on the process flow diagram. As a practical solution to our findings we propose the coexistence of traditional and post-WIMP styles: during normal process conditions, when task completion time is not the primary criteria, interaction via tangible control elements would help developing an accurate process picture while in abnormal situations, in which rapid and effective process intervention becomes crucial, traditional input styles could be used. In this case operators would still benefit from prior process intervention via tangibles. In order to investigate whether the suggested solutions are applicable to real-world scenarios further studies need to be conducted with control room operators.

Ultimately, we suggest that future control room design should reconsider tangible and process-related interaction qualities. For interface design these aspects would then have to be enhanced with and weighed up against digital features. At this point tradeoff considerations as proposed by Jacob et al. [5] provide a helpful guideline.

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