Analysis of Different Types of Navigational Structures for Machine Tool Controlling

Julia N. Czerniak(✉), Tobias Hellig, Alexander Kiehn, Christopher Brandl, Alexander Mertens, and Christopher M. Schlick

Institute of Industrial Engineering and Ergonomics, RWTH Aachen University, Aachen, Germany
{j.czerniak, t.hellig, a.kiehn, c.brandl, a.mertens, c.schlick}@iaw.rwth-aachen.de

Abstract. The rapid technological developments in the manufacturing industry and an increasing demand for more and more complex and individual products has led to the development of modern machine tools from simple tools to highly automated technical products. The trend towards cyber physical production systems will intensify this development in the machine tool sector in context with the so-called fourth industrial revolution. In particular, the increasing quantity of mechatronic components in machine tools has led to a high amount of different functions that need to be controlled by the user. Empirical research has shown that user oriented Human-Machine-Interface-design (HMI-design) reduces error rates and cognitive load for the machine operator and can lead to an increase in effectiveness and efficiency with regard to the interaction. In this paper we introduce a study which points out the impact of user centered design by analyzing the differences of workflow-oriented and function-oriented HMIs. The results of the study show that work task performance can be enhanced by workflow-oriented HMI by improving the time needed and diminishing the number of clicks and errors for specific work tasks.

Keywords: Human-machine-interaction · Function-oriented navigation structure · Graphical user interface · Machine tool controlling · Workflow-oriented navigation structure

1 Introduction

Over the last few years, machine tools have developed into exceedingly complex high-tech systems in order to fulfill the increasing demands that have risen up lately from the manufacturing industry. This trend is set to continue, as machine tools will ascend in their complexity and quantity since cyber physical production systems yield a real-time optimization of value-added chains as a result of intelligent monitoring and decision making processes.

The number of physical input elements on numerically controlled machine tools has approximately tripled since their market launch in the early 1960 s, due to a rising amount of functions the machine needs to fulfill [1]. More specifically, the ever-increasing number of mechatronic parts in machine tools has led to a high amount of

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different functions that need to be operated by the user [2]. However, the corresponding controlling concepts have only been slightly revised, resulting in significant cognitive demand on the user which is attributable to a lack of intuitiveness [3].

Empirical investigations have revealed that, in comparison to a function-oriented design, a workflow-oriented design of a human-machine-interface notably reduces the error rates and cognitive load for the machine operator [1]. Additionally, this design usually has a lower software complexity, reducing the initial training and execution time. Furthermore, regarding the HMI, it can also create a boost in effectiveness and efficiency [4]. In order to properly design an interface, human needs and capabilities already ought to be properly deliberated during the development process. If this recommendation is followed, contemporary workflow-oriented HMI concepts have the ability to improve usability by simultaneously offering a more intuitive handling of the machine and lowering the cognitive load in everyday controlling operations.

A possible approach to designing a workflow-oriented HMI is derived from the information and telecommunications sector. Widely spread on smartphones, application programs (Apps) could be incorporated into interfaces on machine tools. Unfortunately, apps are traditionally characterized by a minimalist structure with only one function. While this makes apps intuitive and easy to use, with reference to the complexity of a machine tool, this concept is limited. However, it is possible to combine several elemental apps to so-called “container apps” so that the reduced app concept can be displayed on a multifaceted HMI. Therefore, this study analyzed the usability for machine tool controlling based on general ergonomic implications for designing Human Machine Systems given in standard series DIN EN ISO 9241.

Taking this concept a step further, there may be cases in which different types of workflows are optimal for different age groups. It is conceivable that the younger generation that was born and grew up during the information era has a better grasp of modern HMI concepts than the elderly and thus has a different understanding according to workflow structures [5]. This phenomenon is dubbed the technology generation effect and could be utilized to construct an individualized adaptive HMI in terms of expected conformity to age-related mental models.

1.1 User-Oriented Human-Machine-Interface-Design

According to DIN EN ISO 9241-12, a graphical user interface (GUI) needs to meet the following seven design aspects in order to be guarantee an efficient and effective usage. Firstly, it needs to display the visual information in a clear and concrete way to enable a simple information intake by the user. Secondly, differentiability of the information is of importance. Also, the information needs to be presented in a compact form, i.e. only relevant information is shown. Additionally, consistency is the key success factor in order to avoid confusion. Furthermore, the attention of the operator needs to be drawn to the relevant information. Lastly, the information presented obviously needs to be easily legible and comprehensible. [6].

Often, a multitude of visual information that needs to be processed is presented to the user. In order to simplify the task of information intake, information can be clustered on the GUI according to the gestalt laws of grouping. These principles, as summarized by Wagemans et al. (2012), were first proposed by gestalt psychologists in the 1920 s and assist in emphasizing the relevant information and distinguishing between the different information clusters. The first principle, the law of proximity, states that objects that are seen as close together are perceived to form a group. The law of similarity asserts that similar objects are grouped together. Similarity can be based on color, shape, shade or various other attributes. Lastly, the law of closure maintains that people see objects (i.e. letters, shapes) as a whole even when they are incomplete. Using these principles, information can easily be grouped on a GUI, helping to direct the attention of the user to the information relevant in the specific context. [7].

Moreover the user can be supported by context sensitive help systems, that are dependent on the current processing status [8], for example greyed buttons, that are not necessarily needed for the actual task.

Furthermore, a GUI should be designed according to the user's attention. To this end, information should be presented in an area of the interface where it is most expected, for example, by placing a close button in the top right corner [6].

1.2 Function-Oriented and Workflow-Oriented Human-Machine-Interface

The complexity of machine tools increases with every passing year as they are required to perform more complex tasks with function-oriented HMIs. However, empirical studies have shown that human mental models are based on actions and not on functions or data types [9]. The traditional function-oriented approach to design a machine tool HMI does not appropriately assist the operator, who is left with a high level of cognitive load. Hence, initial training times need to be prolonged and daily tasks are more inefficient [1]. These problems can be alleviated with a contemporary workflow-oriented approach that assists the user by reducing transfer capacity to his mental model. Thus operating times should decrease in total for workflow-oriented HMI concepts by reducing execution times, the amount of clicks to fulfill the work task, as well as the number of mistakes made during performing the work task.

The field of telecommunication has given rise to a new possibility for designing machine tool HMIs: the app concept. Typical smartphone apps are characterized by their minimalist structure, where every app has a certain purpose and therefore limited functionality. This means an app is easy to operate as the manageable size makes it easy to find functions. However, at the uppermost operating level (i.e. the desktop) the complexity is increased dramatically due to the accumulation of apps. Furthermore, no operating steps are presented to the user, which is critical for a machine tool HMI. Thus, the typical smartphone app concept needs to be adapted in order to be a useful fundament for a user-oriented machine tool HMI. At the most elementary level, where tasks cannot be divided in subtasks any further, the apps concept can be directly adopted. Then, in order to describe more complex tasks, several elementary apps are combined in a container app to create a sequential workflow that can be carried out without much cognitive effort. [1].

Since the user does not need to remember the order of tasks or their position in the whole process and continuously look for them, this app design saves time as well.

If necessary, container apps can then also be combined. This combination of apps ultimately results in the reduction of complexity on the uppermost levels of the HMI even when there are a large number of possible functions while retaining the simplicity of apps in the lower ones. Further, these apps can also be adapted to suit each individual user, for example displaying the most used functions more prominently [10].

2 Method

In order to develop a laboratory study to analyze the impact of different HMI designs on the working performance and the worker's load, a video of a common machine tool workflow of "setting machine coordinate origin" was recorded for a Hermle machine tool with SINUMERIK controlling. The workflow was analyzed based on the Hierarchical Task Analysis (HTA) [11] and was then abstracted to a simplified workflow that can also be handled by novices (Fig. 1). Two different HMIs were implemented, a function-oriented HMI reflecting the current HMI design of the machine tool and a workflow-oriented HMI according to the principals of optimized graphical user interfaces and navigation structures (see Sect. 1.1). The main objective of the study was to test the workflow-oriented HMI compared to the function-oriented HMI design for machine tools. Therefore we used clickable computer-based mockups for both HMI versions. As independent variables we assessed the function-oriented approach in condition 1 and the workflow-oriented approach in condition 2 of the study. The depending variable of the study is *user performance* (distinguished in *execution time*, *number of clicks* to perform the work task and *number of errors*).

2.1 Participants

For the study 19 participants (aged between 20 and 34 years) with an average age of 27 years were tested. Ten of the tested participants were male, whereas 9 participants were female. All participants reported being experienced with mobile devices. About half of all participants reported to be unexperienced in using milling machines, while six participants worked at a milling machine at least once. Table 1 shows the demographic information of the participant group, including self-reported knowledge with milling machines and smart devices.

2.2 Procedure and Task

The study was conducted in a laboratory of the Institute of Industrial Engineering and Ergonomics at RWTH Aachen University. All people participated in both conditions and completed the same task with both mockup versions. The participants were introduced to the task by a verbal description and pictures of the scenario. The participants were given a text-based step-by-step instruction of the workflow to be performed, and sufficient time to become familiar with the workflow. After the participants read the instruction, they started performing the task "Set machine coordinate origin" with the first HMI design. The starting task was permuted between condition 1 and 2

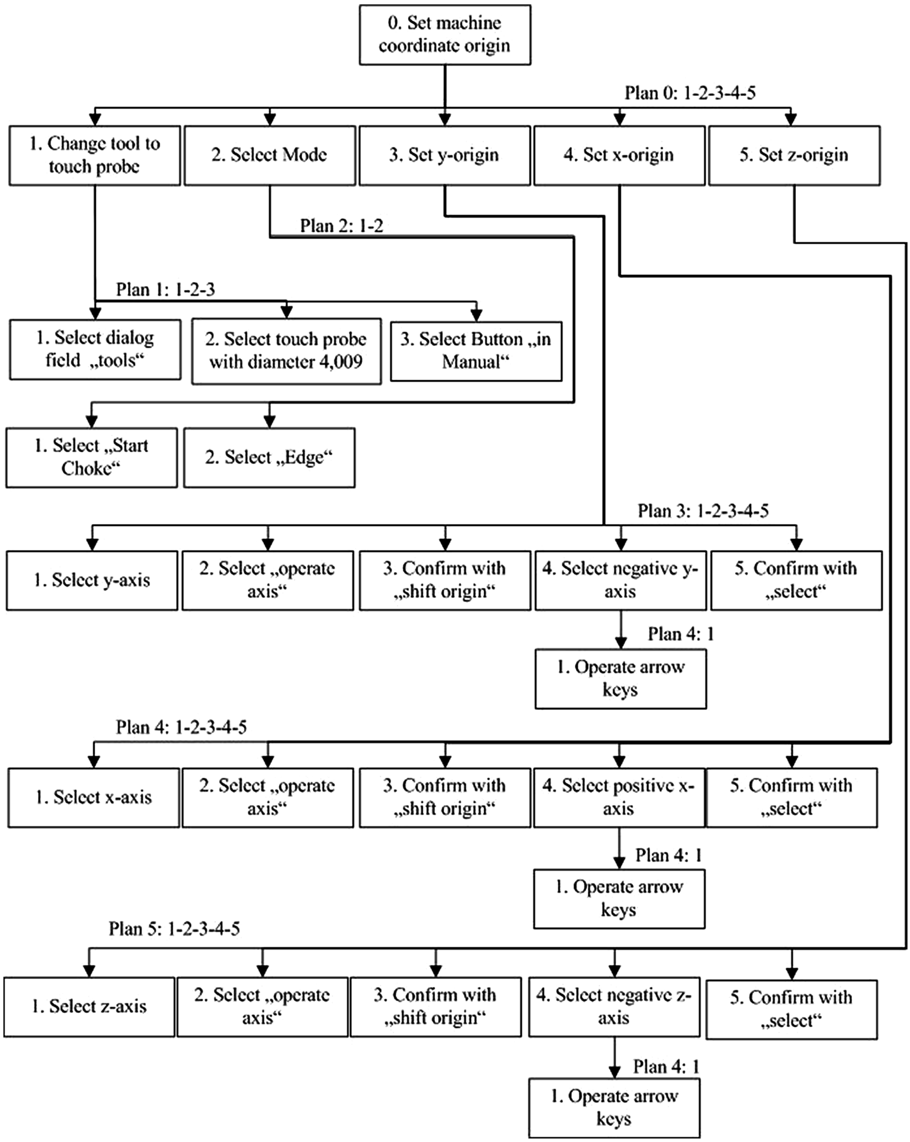


Fig. 1. Selected simplified machine tool workflow “Set machine coordinate origin” for the laboratory study.

for each participant. After performing the workflow on both HMI designs, an additional questionnaire was handed out to collect subjective impressions of each participant with respect to the different HMI designs, supplementing the objective data collected during the task performance.

Table 1. Characteristics of Participants, Mean (and Number)

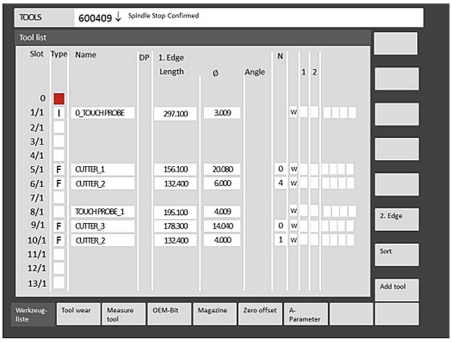
Age	Gender		Knowledge Milling Machine					Knowledge Smart Device	
27	F	M	1	2	3	4	5	1–4	5
(Mean)	(9)	(10)	(5)	(3)	(4)	(7)	(0)	(0)	(19)

Note. M = male; F = female; Knowledge Milling machine and Knowledge Smart Device were counted from 1 = "I have never seen a milling machine/mobile device in my life" to 5 = "I regularly use milling machines/mobile devices".

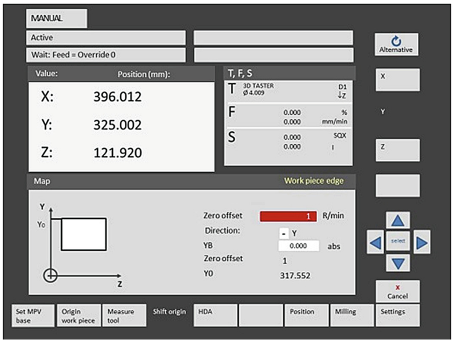
For condition 1 a function-oriented HMI of a milling machine controlling was rebuilt by a computer-based mockup version. For condition 2 a workflow-oriented HMI was designed as a mockup considering gestalt laws of grouping [6, 7], as well as contextsensitive menustructuring [8]. Furthermore, the visual design of the workflow-oriented mockup is based on mobile devices in order to adapt their advantage of intuitivity [12].

Figure 2 shows screenshots of the function-oriented mockup version for condition 1. The buttons to operate the mockup of the function-oriented HMI were arranged in a row at the bottom and in a column at the right edge of the interface according to the interface

(1) Start Screen



(2) Tool Selection

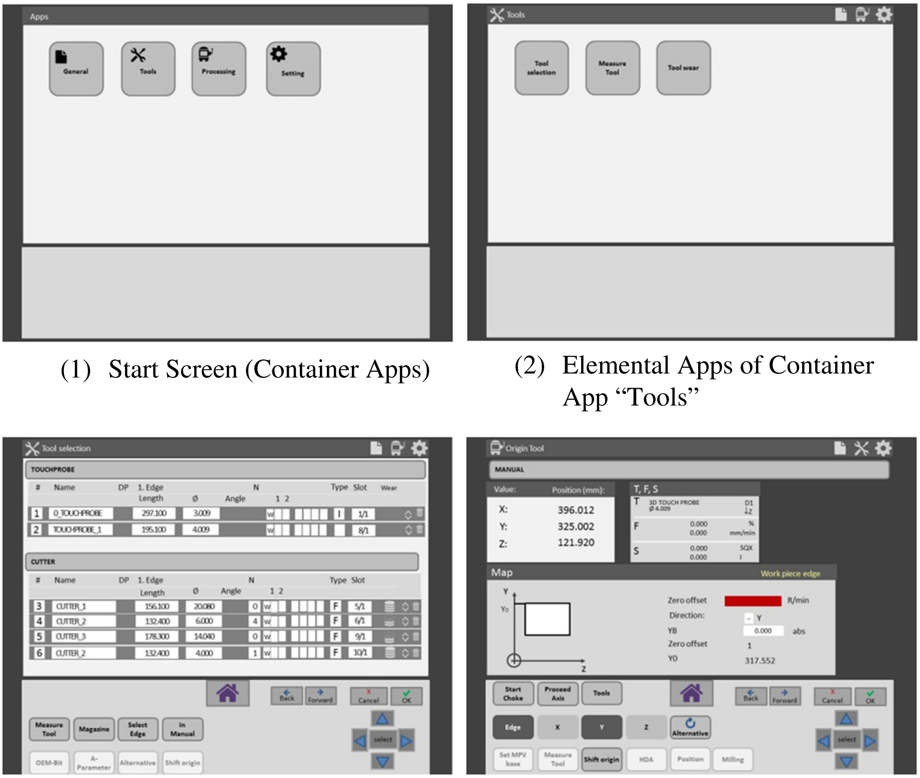


(3) Set axis direction

Fig. 2. Screenshots of the rebuilt function-oriented SINUMERIK-Mockup (condition 1)

layout of the real machine tool (e.g. see screenshot (1) in Fig. 2). In the "tool selection" menu the tools were arranged by their slot in the tool changer (screenshot (2)). Additional elements needed to operate the mockup were implemented by hard buttons on the HMI, e.g. the directional pad, depicted in screenshot (3).

Figure 3 shows the workflow-oriented mockup version realized for condition 2. The start screen in this condition shows several container apps (screenshot (1)) including different apps with elementary functions with the same context (screenshot (2)). In this version we also implemented a control area for all tasks, where all buttons are placed, at the bottom of the interface (see screenshots (3) and (4)). To compare both conditions we maintained the look-alike of the display and all control elements as buttons or the control cross in conformity with condition 1. Buttons belonging to the same context were arranged in proximity to each other according to gestalt principles [6, 7]. The buttons to control the actual workflow part, as well as corresponding operations, were arranged in the top row of the key pad. Selection buttons were placed in the middle row and the bottom row contains functions that do not affect the actual workflow. The menu buttons were greyed out according to context sensitivity [8]. Unlike the interface in condition 1, tools were sorted by type on the first level and by



(1) Start Screen (Container Apps)

(2) Elemental Apps of Container App "Tools"

(4) Tool Selection

(3) Set axis direction

Fig. 3. Screenshots of the workflow-oriented mockup (condition 2)

name on the second level in the tool selection menu instead of slot numbers (3). Buttons that refer to specific tools, e.g. “delete tool” or “tool wear”, were replaced by descriptive icons, which were placed at the end of each tool row.

2.3 Statistical Analysis

Descriptive results were further analyzed with inference statistical methods, to check, if statistically significant differences for the tested HMI types in performing indicators could be proven. A one-way repeated measures ANOVA with a Greenhouse-Geisser correction was conducted to compare the effect of the independent variable function-oriented versus workflow-oriented HMI structure on the dependent variables execution time, clicks and errors at a level of significance of 0.05.

3 Results

For each participant, the execution times in each condition, the number of clicks needed to perform the entire workflow and the number of errors made were collected as dependent variables. Table 2 shows the descriptive results of the 19 participants. Then we calculated the minimum, maximum, mean and standard deviation for each dependent variable (see Table 2 and Fig. 4). Results show that the minimum of the execution time, clicks and errors is lower in condition 1 compared to condition 2. The maximum of the execution time, clicks and errors is higher in condition 1 than in condition 2. For condition 2, the mean and standard deviation is lower for each dependent variable.

Table 2. Descriptive Statistics for Condition 1 and 2 of the *Execution times*, *Clicks*, and *Errors*

	N	Min	Max	Mean	Std. Error	Std. Deviation
Execution time Condition 2 [sec]	19	84.00	556.06	202.21	27.59	120.25
Execution time Condition 2 [sec]	19	43.28	329.13	156.13	15.82	68.97
Clicks Cond.1	18	21	96	32.33	4.45	18.89
Clicks Cond.2	18	4	53	27.61	2.57	10.91
Errors Cond.1	18	2	77	14.94	4.54	19.28
Errors Cond.2	18	0	33	9.22	2.18	9.23
Valid N (listwise)	18					

Regarding the execution time, the participants needed 202 s in average with a standard deviation of 120.248 to perform the working task with the function-oriented HMI, while the workflow-oriented HMI led to an average execution time of 156 s with a standard deviation of 68.97. The better performance of the workflow-oriented HMI is confirmed by the mean values of the clicks and errors. Concerning the clicks, participants needed 27.61 clicks on average (SD = 10.907) to perform the given task with

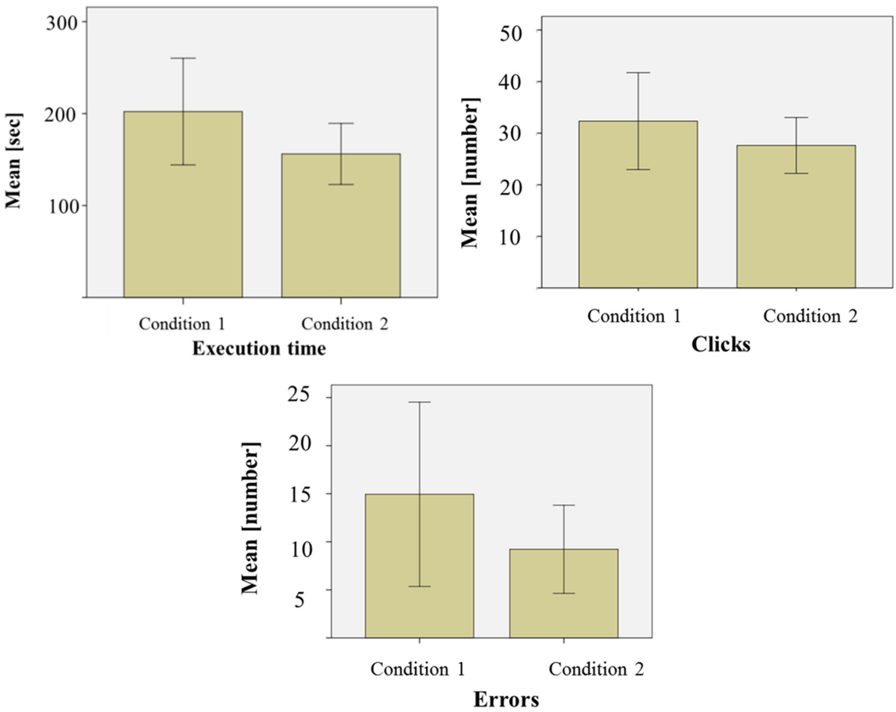


Fig. 4. Mean and Standard deviation of the Execution times in seconds (upper left), number of clicks (upper right) and number of errors (bottom center) in Condition 1 and 2

the workflow-oriented HMI and 32.33 clicks on average (SD = 18.89) to perform the same task with the function-oriented HMI. The mean value for errors made by all participants during the working task was 14.94 in condition 1 (SD = 19.28) and 9.22 in condition 2 (SD = 9.23). The evaluation of the subjective questionnaire approves these findings. 73.68 % of the participants answered, that the workflow-oriented condition (2) was more intuitive and clearly arranged than the function-oriented condition (1).

However, the ANOVA determined that neither the mean length of execution time did differ statistically significantly ($p = 0.189$) between time points ($F(1.000, 18.000) = 1.861$, $p > 0.05$). Nor the mean number of clicks differ statistically significant ($p = 0.378$) between time points ($F(1.000, 17) = 0.819$, $p > 0.05$), nor the mean number of errors differ statistically significant ($p = 0.288$) between time points ($F(1.000, 17) = 0.288$, $p > 0.05$).

4 Discussion

As it becomes obvious, the mean execution time is 46 s lower in condition 2 (workflow-oriented) than in condition 1 (function-oriented). These descriptive results point out that the workflow-oriented HMI leads to an average time saving of about 20 %

in comparison with the function-oriented design. Also, the standard deviation of execution time in condition 2 is considerably lower, which allows a more efficient time planning in production planning and scheduling by using workflow-oriented HMIs. The mean of clicks and errors can also obtain as an initial estimate for the improvements of workflow-oriented HMI approaches. Both means (as well as standard deviations) were lower in condition 2 than in condition 1 (4.72 on average for clicks and 5.72 on average for errors). Most of the clicks and errors were made in the workflow step "set axis direction" for all axes with the arrow keys of the directional pad, which nevertheless was adopted from the function-oriented approach and could be replaced by a more intuitive control element, for example a touch button, which allows a direct input of the axis value. To eliminate additional errors, for example made when selecting one of the axes, an enhanced visualization of the current workflow, i.e. depiction of the next task to perform, will improve the user orientation and will result in lower error rates. None of the dependent variables was statistically significant, which can be explained by characteristics of the test design of this preliminary study. Our study only comprised a single and brief work task with low complexity that was intended to be solved by the participants without any previous knowledge by just executing the written step-by-step instruction. Furthermore the average task execution time only lasted 179 s. According to the descriptive findings a subsequent study will be conducted, in which disturbance variables are going to be eliminated. Beyond that the rework of the workflow-oriented HMI, based on the results of the preliminary study and especially on the analysis of the subjective questionnaires, should lead to meaningful and significant results.

5 Conclusion

Prior research has documented the advantaged of workflow-oriented HMI design to support the user by carrying out human thinking structures [1]. However, these works did not study the actual effects caused by redesigning HMIs using an app concept empirically. This study can be seen as an explorative preliminary study to gain first important findings of the impact of workflow-oriented HMI design. In this study we tested effects among a group of novices for the work task "Set machine coordinate origin". The descriptive analyzes revealed that the workflow-oriented HMI resulted in a decrease of all dependent variables (execution time, clicks, errors). These findings extend those of Herfs et al. (2013), confirming that the work task becomes easier to solve for the participant with a workflow-oriented HMI. In addition, the improvements noted in our study were unrelated to gender. This study therefore leads to the conclusion that the benefits from workflow-oriented HMIs will be valid across a wide range of the HMI's users. However, some limitations are worth noting. Although our study has descriptively shown an improvement of performance, results only show a tendency, but no significance. To emphasize inference statistically effects, future work should therefore consider conducting an extended, optimized study with a longer procedure time as well as more short term task and an optimized HMI design. Moreover, further work should incorporate age-differentiated studies to analyze a possible Generation effect.

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