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TECHNICAL NOTE

Should firms use digital work instructions?—Individual learning in an agile manufacturing setting

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Email: peter.letmathe@rwth-aachen.de**Funding information**Deutsche Forschungsgemeinschaft, Grant/Award Number: GRK 1491
Graduiertenkolleg Anlaufmanagement**Handling Editor:** Alan Mackelprang**Abstract**

New technological innovations in robotics, automation, and digitization enable agile manufacturing, smaller lot sizes, and quicker changes to the product and the production process. In such environments, learning is important, since workers must learn new tasks and adapt to frequent changes quickly. In an experimental study, we compare digital work instructions with traditional paper-based ones, the latter still being common in today's quality management systems. Our analysis is based on subjects working in the demonstration factory of a large German university in a realistic work environment; it, therefore, guarantees high internal and external validity. We show that digitally animated, interactive work instructions are an effective way to foster faster learning and enhanced performance when new manufacturing tasks are being carried out. Our results indicate that a combination of digital and traditional paper-based instructions does not yield any advantages over a sole reliance on digital learning.

KEYWORDS

agile manufacturing, learning, work instructions

Highlights

- Digital work instructions lead to superior manufacturing performance compared with paper-based instructions.
- A combination of digital and traditional paper-based work instructions does not yield any advantages over a sole reliance on digital learning.
- In agile manufacturing settings, companies should invest in digital learning.

1 | INTRODUCTION

Current technological developments such as innovations in robotics, automation, and digital interconnectivity enable an agile form of manufacturing which allows smaller lot sizes and more frequent changes to product designs and production processes (Holmström et al., 2019; Jain & Jain, 2001; Yusuf et al., 1999). However, even in automated

and agile production systems, it is expected that human workers will remain a focal part of a production system (Alavi et al., 2014). In such environments, since targeted human learning is crucial for fully exploiting the potentials of agile manufacturing, this emphasizes the importance of mechanisms of knowledge transfer, for example, as codified in work instructions. Therefore, this paper analyzes the effectiveness of different forms of work instructions for

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learning new tasks. It answers the question “Should firms use digital instructions? And if yes, how should they implement them?” Interestingly, this study reveals that firms should implement digital instructions radically by replacing paper-based instructions rather than incrementally by adding them to existing paper-based instructions.

In particular, when workers have to learn new or quickly changing tasks, digital work instructions may be of great value. According to Kock's (2005, 2009) Media Richness and Naturalness Theory, it can be expected that the higher the similarity of the depiction in the instruction and the real-world objects, the easier they are to cognitively process. In a similar way, Dual Coding Theory (Clark & Paivio, 1991; Paivio, 1990) and the Theory of Multimedia Learning (Mayer, 1997; Mayer, 2001) say that learning occurs better when information is presented in verbal and visual form, so that it can be processed through different cognitive channels simultaneously. The closer a set of instructions is to a causal, executable mental model, the more cognitive capacity can be used for actual learning (Schnotz et al., 1999). Compared with paper-based work instructions, animated, interactive instructions regularly offer more information and are closer to a causal mental model and thereby reduce cognitive demands.

In this vein, a large variety of systems have been invented and numerous patents exist for digitally animated and interactive work instructions rather than relying on hardcopy (paper-based) work instructions, such as technical drawings (Beatty et al., 2004; Dong-Sik et al., 2012; Goss, 2001; Krauter et al., 2016; Senesac, 2017; Sun et al., 2010). Nonetheless, digitally animated, interactive work instructions have not yet found their way onto the mainstream shop floor. One reason for the hesitancy of the industry may be that little research has clarified whether such new forms of work instructions are superior to traditional paper-based ones and how potential benefits of digitally animated, interactive work instructions may foster operational excellence (Yusuf et al., 1999). Moreover, no existing literature has so far tested the effectiveness of digital work instructions for learning new tasks in manufacturing settings. The research project at hand gave us the unique opportunity to conduct such a study in a typical manufacturing setting.

2 | DIGITALLY ANIMATED, INTERACTIVE WORK INSTRUCTIONS

Digitally animated, interactive work instructions provide different means of enhancing task understanding and learning new manufacturing or assembly tasks as compared with paper-based technical drawings. To appropriately measure performance when learning a new manufacturing

task, we use the number of defects and the required time as dependent variables to measure performance in line with the related literature (e.g., Benkard, 2000; Letmathe et al., 2012; Michas & Berry, 2000; Schwan & Riempp, 2004; Terwiesch & Bohn, 2001). These two indicators can be measured accurately on the individual level and determine the overall quality and timeliness of industrial production systems. Both performance indicators are expected to be influenced by different instructions as outlined in the following.

First, animated work instructions display moving images in contrast to still depictions. As Nerdel (2002) explained, learning from a moving image relieves working memory of the learner because he or she does not need to form an imagination of the movement. Therefore, cognitive capacity can be utilized solely for understanding and learning of the process and the correct processing into the long-term memory. In addition, any misinterpretation of static representations of movements, for example, arrows, can be prevented by unambiguous moving images (Nerdel, 2002; Park & Hopkins, 1992; Salomon, 1979). Additionally, well-designed digitally animated, interactive work instructions can represent 3D-images from all sides (compared with complex technical drawings) and depict detailed movements.

Second, interactivity of digital work instructions gives the learner self-control, which may increase motivation and learning success (Euler, 1994; Nerdel, 2002; Schnotz et al., 1999). Moreover, interactive instructions can increase learners' engagement with the task and direct their attention to the relevant aspects of complex tasks, which helps to reduce cognitive load and to utilize cognitive capacity for the actual learning process (Ngu et al., 2009).

Third, as mentioned in the introduction, Dual Coding Theory (Clark & Paivio, 1991; Paivio, 1990) and Multimedia Learning Theory (Mayer, 1997; Mayer, 2001) state that learning occurs better when information is presented in verbal and visual form so that it can be processed simultaneously (Mayer, 1997; Schnotz et al., 1999). The possibility of including verbal cues directly within the presentation of each work step is an inherent advantage of digitally animated, interactive work instructions (Michas & Berry, 2000; Spangenberg, 1973). While it would generally be possible to add verbal explanations to a paper-based technical drawing, it is hard to realize the logical proximity of written text and visual depiction of a work step, especially because technical drawings often need to depict multiple actions within a single drawing in order to sustain clarity.

From these three lines of argumentation follows that digitally animated and interactive work instructions are expected to be superior to paper-based technical drawings. Hence, firms face the question of whether providing workers with both kinds of instructions at the same time leads to even better performance. The simultaneous

provision of both types of instructions combines the best of both representations, that is, getting a quick overview with paper-based technical drawings and a detailed step-by-step manual in the form of digitally animated, interactive instructions. Individual learners are able to choose what best suits their needs and what is most appropriate for the given task (Ainsworth, 2006).

However, the simultaneous provision of different forms of instructions also poses a higher cognitive load on workers (Eysenck & Thompson, 1966; Goodell et al., 2006). Ainsworth (2006) argued that providing individuals with multiple redundant representations of assembly steps leads to information overload or distraction. This so-called “split attention effect” leads to higher mental effort and thus a longer processing time in order to process the given information (Ainsworth, 2006). In a similar situation, Letmathe et al. (2012) found that combining explicit knowledge transfer with tacit knowledge transfer leads to inferior performance in comparison to purely explicit knowledge transfer. Such an information overload may impede actual learning of new tasks and thereby the attained performance (Letmathe & Zielinski, 2016). This also hints at the drawbacks of providing workers with too much information.

3 | EXPERIMENTAL DESIGN

3.1 | Experimental setting

We test the performance effects of digitally animated and interactive work instructions through a laboratory experiment in an industrial manufacturing setting. This means that, rather than relying on purely theoretical, computer-based tasks which serve limited purposes, we experimented on a factory shop floor with real manufacturing equipment and tasks. In contrast to field data, laboratory experiments can provide proof of clear causal relationships in a controlled environment. For this study, we created a laboratory-like controlled environment in the factory of the Demonstrationsfabrik Aachen (DFA)—the demonstration factory belonging to the campus of a major German university of technology. Details of this environment will be explained in the next section.

A high internal validity as well as reliability are given in laboratory experiments due to their controlled environment (Letmathe & Röbler, 2019). A common point of criticism towards laboratory experiments is that external validity is limited. This topic has received extensive attention, especially with regard to the recruitment of subjects from student pools, and there is agreement that accurate theories should hold for student populations as well as for others (Peterson, 2001). Specifically with regard to learning, there is no evidence that students as subjects

lead to different results than employees who have gone through the dual education system that is common in Germany (Letmathe et al., 2012). The dual education system is considered to be one of the major competitive advantages of German industrial companies (BMBF, 2015). A completed apprenticeship or a bachelor's degree, which are achieved by more than 80 percent of German employees, are roughly equivalent to a bachelor's degree from a community college in the US, but it contains a much higher practical component during the programs which usually last for 2–3 years. Since this experiment is conducted in a factory, external validity is higher compared with classical computer-based tasks. The workstations, the tools and parts, and also the task itself represent the actual factory setup around which we built a controlled laboratory environment. Moreover, with the task at hand, the number of defects and the required time can each be measured separately.

3.2 | Experimental treatments

Three experimental treatments served to compare the effectiveness of digitally animated, interactive work instructions and paper-based technical drawings when assembling small-scale metal products. In this section, we first describe the basic procedure of the experiment, which remained the same for each participant independently of the assigned treatment, before we turn to the manipulations of each treatment.

Each subject attended a session that took roughly 60 min in total. The task was to build four identical metal pencil holders with the help of the provided material, as a typical example of a simple manufacturing task relying on manual labor. One pencil holder consisted of eight metal pieces which had to be assembled with five different types of crosshead and Allen screws (18 screws in total) using three different kinds of screwdrivers or Allen wrenches (see Appendix A for a photo of a completed pencil holder). Each subject was equipped with the three required screwdrivers/Allen wrenches, an ample amount of screws of all needed types and their treatment-specific set of instructions. The sessions took place in the factory of the DFA, a demonstration factory which is located on the authors' university's campus. Being one of the most advanced research factories worldwide, it serves the purpose of implementing and testing state-of-the-art production environments in a highly realistic but controllable factory setting. The four workstations of the factory were provided on days when no production and no other work was taking place there, a situation which guaranteed that there would be no disturbances. We rented the factory shop floor for these days to ensure the controlled

environment of a laboratory when conducting the experiment. Each workstation was surrounded by separating walls, so that subjects were not able to see anything outside their own workstation; particularly, they were not able to observe each other. For each treatment, that is, for those subjects who were equipped with the same set of instructions, there were six sessions. Each subject attended one of these sessions. The sessions were scheduled in such a way that neither the time of day nor the idiosyncrasy of a particular day, for example, any singular circumstances influencing a subject's mood, had an influence on the results. The experiment took place over the course of three consecutive days with six sessions scheduled per day. For every treatment, the sessions were equally spread over all six possible time slots, so that no treatment was concentrated on any particular time of the day. In addition, for each treatment, the sessions were split 50:50 between 2 of the 3 days, meaning that three sessions were scheduled to 1 day and three sessions were scheduled to another day. When signing up for the experiment, the subjects chose a time window that determined their assignment to a particular treatment. This allocation mechanism was not known to the subjects, thus ensuring random treatment allocation.

At the beginning of their assigned session, subjects entered the factory and drew a random number to be allocated to one of the four workstations (Step 1). Once every subject was standing at their respective workstation, the experimenter gave a short introduction with regard to the course of the experiment (Appendix B). This introduction included brief information on the task, the provided materials and work instructions, the performance criteria, and the payment scheme (Step 2). After the introduction, subjects were given the chance to report on any problems at their workstation before starting to work on the task (Step 3). However, no problems occurred. The subjects were then handed the parts for the first pencil holder and their time started as soon as they received the parts (Step 4). The time was taken by an assistant of the experimenter individually for each subject with the help of stopwatches. When a subject had finished the assembly of the first pencil holder, they raised their hand and the time was immediately stopped (Step 5). The pencil holder was then collected by the experimenter's assistant. Each pencil holder was assessed with regard to potential defects and subsequently disassembled by the experimenter and the assistant (Step 6). If the pencil holder was assembled correctly, zero quality deficit points were assigned. The following shortcomings were considered a defect and counted as deficit points: One point per missing part, per part mounted in the wrong location or not oriented correctly, per missing screw, per screw which was of the wrong type, per screw

not fully screwed in. Subjects were handed the parts for the next unit immediately after a completed pencil holder had been collected by the assistant. The steps four to six happened four times, which means that each subject assembled four pencil holders. The subjects did not receive any feedback on their performance. After a subject had finished all four pencil holders, they filled out a post-experimental questionnaire asking for a self-assessment of their previous skills and experience before starting the experiment regarding craftsmanship, technological understanding, as well as experience with technical drawings and with digital work instructions (Step 7) (Letmathe et al., 2012). In addition, the questionnaire included items on invested mental effort (Kablan & Erden, 2008; Ngu et al., 2009; Paas, 1992), intrinsic motivation (Grant, 2008), persistence (Deater-Deckard et al., 2005; Guan et al., 2006), how helpful the respective instructions were with regard to task understanding (Moreno et al., 2001), and lastly demographics, such as program of study, current semester, age, gender (Letmathe et al., 2012) (Appendix C). After completing the questionnaire, subjects were guided toward the exit and received their individual payment (Step 8). Table 1 displays the procedure of the experiment.

The minimal amount of interaction of the experimenter with the subjects limited the potential experimenter bias, a common threat to the internal and external validity of experimental studies (Venkatesan, 1967). In addition, a printout of the payout table was provided at each workstation which explained the performance-dependent payout. Each participant received a base payment of €5 plus a performance-dependent bonus. The bonus depended on the number of defects (deficit points) and the time required to build each of the pencil holders. For each pencil holder, an individual bonus was assigned. In order to get a bonus, subjects had to focus simultaneously on the performance dimensions "defect" and "time." Excelling in one of the two

TABLE 1 Experimental procedure

Step 1	Random allocation of subject to one of four workstations.
Step 2	Introduction: information on task, provided materials and work instructions, performance criteria, and payment scheme.
Step 3	Chance to report problems.
Step 4	Handing out parts and assembly of pencil holder.
Step 5	Finishing of pencil holder indicated by raising hand.
Step 6	Collection, assessment, and disassembly of pencil holder by experimenter and assistant.
Step 7	Post-experimental questionnaire.
Step 8	Leave towards exit and receive individual payment.

dimensions while neglecting the other did not lead to a bonus. The theoretically attainable maximum payment equals €19 for all four pencil holders, but was not attained by any of the subjects. The payment scheme is provided in Appendix D.

There were three treatments, which differed with regard to the work instructions that a subject was equipped with; paper-based technical drawings (Treatment I—“paper treatment”), digitally animated, interactive work instructions (Treatment II—“digital treatment”), and both (Treatment III—“both treatment”). Illustrations of the different instructions are provided in Appendix E. The digital work instruction is a proprietary development of the DFA and displays individual assembly steps on a digital touchscreen. It allows users to zoom in and out and change the angle in a continuous way so that a full three-dimensional image of every part at any point of the assembly process can be viewed. The user also chooses to proceed to the next assembly step by touching a small arrow in the bottom right corner and can jump back to the previous step by touching an arrow in the bottom left corner. In addition, the user can directly choose a specific assembly step by selecting it from a list of all assembly steps, which is provided at the bottom of the screen in the form of miniature images of the respective step. Beyond the application in this experiment, the technology allows the right set of instructions to be retrieved for any variant of the produced products at the right time with the help of RFID tags. This application is a first step toward showing what an increased usage of digital media on the shop floor can achieve. Even though the experiment does not include elements of augmented or virtual reality, the digital instructions yield some of the same benefits, such as realistic depiction of assembly steps, three-dimensional impressions, and intuitive controls (Gilbert, 2016). Further information about the experimental procedure is provided under the following link: <https://www.controlling.rwth-aachen.de/cms/Controlling/Forschung/Forschungsprojekte/Weitere-Informationen/~pptdr/Digital-Work-Instruction/?lidx=1>

This supplementary material also includes the software to run the digital work instructions. With this demo version, the functionality of the instructions can be perfectly reviewed. However, details of the depiction depend on the used device and may differ slightly from the depiction on the screens in the DFA Demonstrationsfabrik Aachen GmbH, which were used in the experiment. This may particularly apply to the interaction via touchscreen and the depiction of individual assembly steps at the bottom of the screen. Additionally, we also uploaded photos from the demonstration factory and the workplaces where the experiment was carried out. We want to point

out that these photos were not taken during the experiment in order to avoid any influence on the participants in the experiment.

In contrast, the paper-based technical drawings were provided on a printout with exactly the same assembly steps. The technical drawings included depictions of the pencil holder at three different points in time during the assembly process to show the required next assembly steps. These drawings depicted the different metal parts and screws. The screws were specifically labeled so that they could be identified unambiguously. A three-dimensional impression was evoked with the help of specific drawing angles and support lines. However, naturally, the two-dimensional sheet of paper was limited in its capacity to depict a three-dimensional pencil holder. In summary, the two sets of instructions provided the same information but with the help of different media—digital instructions versus paper-based instructions. The digital instructions were therefore able to include the advantages of animation and interaction.

3.3 | Sample description

Sixty-six participants took part in the experiment. The observations for two subjects had to be dropped due to individual problems with understanding the task and the planned course of the experiment. This results in a data set of 64 subjects, out of which 20 were allocated to Treatment I (“paper treatment”), 22 to Treatment II (“digital treatment”), and 22 to Treatment III (“both treatment”). There are no missing values for any of the variables.

The subjects from different programs are enrolled at a large German university and were recruited from a subject pool deliberately set up for economic experiments. Treatments are similar with regard to the percentage of females, of students from technical programs, and with regard to other control variables. Hence, the random treatment allocation is not biased with regard to important subject characteristics. Table 2 provides an overview of the sample.

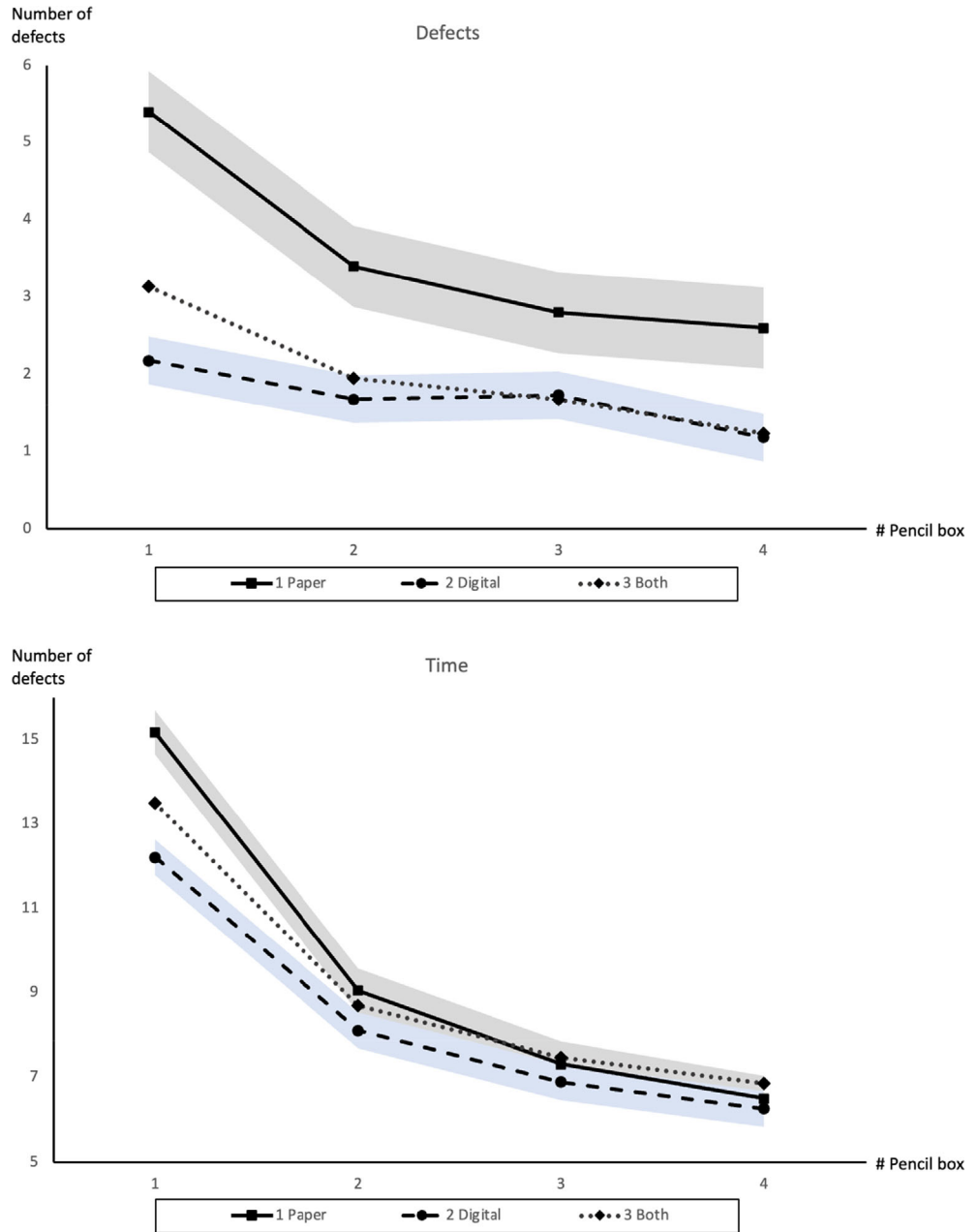
3.4 | Variable definitions

The two central dependent variables, relevant for testing the hypotheses, are (i) number of defects to measure quality (see Section 3.2 “Experimental treatments”) and (ii) time, which is the total time a subject took to assemble the respective pencil holder. Assembly times were measured exact to the second and afterward converted to a decimal fraction of minutes in order to enable an easy interpretation.

TABLE 2 Overview of the sample

Sample/participants	Number of subjects	Females	In technical program	Mean age (in years)
Total (N)	64	27 (42%)	38 (59%)	22.98
- Out of which “paper” treatment	20	8 (40%)	11 (55%)	23.35
- Out of which “digital” treatment	22	9 (41%)	16 (73%)	23.32
- Out of which “both” treatment	22	10 (45%)	11 (50%)	22.32

FIGURE 1 Learning curves—Defects (deficit points) and time (in minutes)



Independent variables of interest are dummy variables for the treatment allocation. There is one variable for each treatment, which equals 1 if a subject is in this treatment and 0 otherwise. In addition, the number of the pencil holders represents an independent variable to

control for the number of repetitions that a subject has gone through and to analyze learning over the course of the experiment. In addition to these variables, we used dummy variables for each pencil holder and dependent variables for the supplementary analyses (Appendix C,

Panel C2), which were collected in the post-experimental questionnaire (see Appendix C, Panel C1).

4 | RESULTS

4.1 | Descriptive statistics

When analyzing the data from the experiment, it is first to note that learning effects can be observed for subjects from all treatments. When repeating the task, the required time as well as the number of defects were reduced (Figure 1). The shaded bands represent the *SE* for the paper and the digital treatment respectively. The curves are in line with past empirical studies on organizational learning and appear to be similar to classic learning curves in manufacturing environments (Benkard, 2000; Wright, 1936).

Table 3 shows the average number of defects and the average minutes needed to assemble a respective pencil holder for each treatment, individually for each pencil holder, and across all four-pencil holders. *SD* are provided in parentheses below the corresponding mean value. For all treatments, the needed time and the number of defects are lower for later units than for earlier ones, with only one exception in treatment II (“digital treatment”), where the number of defects minimally increases from unit two to unit three. In addition, subjects from the digital treatment make fewer mistakes than subjects from the paper treatment (1.69 vs. 3.55) and take less time (8.37 vs. 9.52 min). These large differences in performance between groups with different instructions demonstrate the huge potential of digital solutions in manual labor tasks on the shop floor. For example, subjects with digital instructions made only about half as many mistakes as subjects with paper-based technical drawings while also being faster. These effect sizes indicate that digitally animated, interactive work instructions

can be an effective means for overcoming the trade-off between quality and time. This trade-off is an important challenge for operations managers in the context of organizational learning in agile manufacturing environments with frequent production changes (Baumers & Holweg, 2019; Letmathe & Röbler, 2016; Terwiesch & Bohn, 2001; Yin et al., 2017).

4.2 | Inductive statistics

Our data set is analyzed with generalized estimating equations. The analyzed dependent variables are defects (deficit points) and time (assembly time per pencil holder). As reported in Section 3.3, our panel consists of 64 subjects (panel variable) with four observations (four pencil holders) per subject (time-variable). This leads to a total number of 256 observations.

The analysis of variance (ANOVA) showed that treatments differed with regard to their performance for defects at a significant level ($F = 6.40, p = .002$) and for time at a marginally significant level ($F = 2.52, p = .083$). Moreover, the ANOVA confirms that learning takes place, indicated by significant changes in performance over time regarding defects ($F = 3.36, p = .020$) and time ($F = 57.15, p < .001$). The interaction term is not significant for defects ($F = 0.37, p = .900$) or for time ($F = 0.76, p = .598$). Following from this, the learning rates do not differ between treatments.

Table 4 contains the results for the general estimation equations, which analyze the influence of the digital treatment and the “both” treatment compared with the paper treatment as the base treatment. Columns 1 and 3 report the results for the digital and “both” treatments without considering interaction effects. Columns 2 and 4 also contain the results for the interaction effects of the individual pencil holders with the individual treatments.

TABLE 3 Descriptive statistics^a

		Pencil holder 1	Pencil holder 2	Pencil holder 3	Pencil holder 4	All pencil holders
<i>Paper treatment</i>	Defects (deficit points)	5.40 (5.41)	3.40 (4.36)	2.80 (4.50)	2.60 (4.25)	3.55 (4.70)
	Time (in minutes)	15.18 (5.67)	9.06 (2.30)	7.32 (2.09)	6.51 (1.35)	9.52 (4.71)
<i>Digital treatment</i>	Defects (deficit points)	2.18 (2.89)	1.68 (2.88)	1.73 (3.13)	1.18 (2.87)	1.69 (2.92)
	Time (in minutes)	12.22 (5.57)	8.11 (2.45)	6.90 (1.94)	6.27 (1.34)	8.37 (3.96)
<i>“Both” treatment</i>	Defects (deficit points)	3.14 (3.72)	1.95 (3.06)	1.68 (2.75)	1.23 (2.20)	2.00 (3.02)
	Time (in minutes)	13.50 (5.63)	8.71 (2.93)	7.47 (2.52)	6.87 (2.09)	9.14 (4.38)

^aMean values (and standard deviation) per pencil holder and treatment.

TABLE 4 Comparison of digitally animated, interactive work instructions alone and in combination with paper-based technical drawings to only paper-based technical drawings^a

Comparison of digital/both with paper treatment	Defects (1) (2)	GEE		
		Time (3) (4)		
Digital treatment	−0.865*** (−5.13)	−0.906*** (−5.22)	−0.152** (−2.07)	−0.217*** (−2.60)
Both treatment	−0.563*** (−3.69)	−0.543*** (−3.53)	−0.060 (−0.84)	−0.118 (−1.44)
Pencil holder	−0.270*** (−9.49)		−0.264*** (−14.45)	
Pencil holder 2 (PH2)		−0.463*** (−6.50)		−0.516*** (−8.89)
Pencil holder 3 (PH3)		−0.657*** (−6.48)		−0.922*** (−6.48)
Pencil holder 4 (PH4)		−0.731*** (−6.11)		−0.847*** (−9.26)
PH2 * Digital treatment		0.202* (1.68)		0.106 (1.27)
PH3 * Digital treatment		0.423 (2.59)		0.159 (1.42)
PH4 * Digital treatment		0.118 (−0.56)		0.180 (1.39)
PH2 * Both treatment		−0.103 (−0.09)		0.078 (0.96)
PH3 * Both treatment		0.034 (0.21)		0.138 (1.26)
PH4 * Both treatment		−0.207 (−1.02)		0.172 (1.37)
Constant	1.951*** (18.90)	1.686*** (17.53)	2.918*** (47.00)	2.720*** (47.40)
Chi-square	120.41***	149.39***	213.09***	295.98***
N	256	256	256	256

^aThe GEE includes dummy variables for digital and the “both” treatment and the interactions with the pencil holders. Dependent variables are the number of defects (deficit points) or the required time per pencil holder, respectively. Negative coefficients indicate that the number of defects is smaller or the required time is less in comparison to the paper treatment. The numbers in the parentheses contain the z-values.

* $p < .10$, ** $p < .05$, *** $p < .01$, z-value in parentheses.

TABLE 5 Comparison of digitally animated, interactive work instructions alone and in combination with paper-based technical drawings to only paper-based technical drawings^a

Comparison of digital and both treatment	Defect (1) (2)	GEE		
		Time (3) (4)		
Both treatment	0.275 (1.54)	0.363* (1.93)	0.092 (1.23)	0.100 (1.18)
Pencil holder	−0.266*** (−6.29)		−0.242*** (−11.00)	
Pencil holder 2 (PH2)		−0.260** (−2.30)		−0.410*** (−7.00)
Pencil holder 3 (PH3)		−0.234 (−1.59)		−0.571*** (−7.25)
Pencil holder 4 (PH4)		−0.613*** (−3.21)		−0.667*** (−7.38)
PH2 * Both treatment		−0.212 (−1.39)		−0.027 (−0.34)
PH3 * Both treatment		−0.390* (−1.91)		−0.021 (−0.19)
PH4 * Both treatment		−0.325 (−1.24)		−0.007 (−0.06)
Constant	1.095*** (7.23)	0.780*** (5.41)	2.724*** (39.85)	2.503*** (41.03)
Chi-square	41.87***	52.31***	122.51***	167.88***
N	176	176	176	176

^aThe GEE includes dummy variables for the “both” treatment and the interactions with the pencil holders. Dependent variables are the number of defects (deficit points) or the required time per pencil holder, respectively. Negative coefficients indicate that the number of defects is smaller or the required time is less in comparison to the paper treatment. The numbers in the parentheses contain the z values.

* $p < .10$, ** $p < 0.05$, *** $p < .01$, z-value in parentheses.

Table 4 reports significantly more defects for subjects from the paper treatment than for subjects from the digital treatment and the “both” treatment. This effect is

highly significant with and without considering interaction effects ($p < .001$ for both columns and both treatments). Hence, the results are fairly robust even when

interaction effects are considered. It is noteworthy that all but one interaction effect are not significant. Only the interaction effect of pencil holder 2 and the digital treatment (PH2 * Digital treatment) indicates a weakly significant relation ($p = .093$). Similarly, subjects from the digital treatment perform the task in a shorter time ($p = .038$ without and $p = .009$ with interaction effects). However, results are not significant for the “both” treatment. With regard to time (column 4), none of the interaction effects are significant. Therefore, we conclude that well-designed digitally animated, interactive work instructions are superior to paper-based technical drawings when learning new manufacturing tasks: Digital instructions lead to shorter processing times while reducing the number of defects at the same time. When digital and paper-based work instructions are combined, they lead to less defects but do not significantly reduce the processing times compared with the base treatment.

Table 5 shows that subjects who were able to draw on both sets of instructions did not perform better than subjects who were only equipped with the digital instructions either with regard to the number of defects or with regard to the processing time. Only when interaction effects are taken into account, the “both” treatment increases (!) the number of defects on a weakly significant level ($p = .054$). However, this effect is partially offset by the interaction effects with only one of them being weakly significant (PH3 * Both treatment, $p = .056$). Hence, we do not find support for a complementarity of technical drawings and digitally animated, interactive work instructions. In contrast, performance is not improved further by providing subjects with additional information beyond the digital instructions.

Summarizing the results, we can state that digitally animated, interactive work instructions increase quality by reducing the number of defects and reduce the processing times simultaneously. The supplementary use of paper-based work instruction does not improve either performance indicator.

5 | DISCUSSION

This study demonstrates the potential of digital technologies in agile manufacturing environments through an experiment in a factory environment. By using digitally animated, interactive work instructions, employee performance in an assembly task can be improved with regard to production quality and time simultaneously when confronted with new production tasks. However, combining digital instructions with paper-based instructions is not beneficial.

Summarizing the paper's findings, we first find that subjects performed significantly better in a new assembly

task with regard to the number of defects and the required time when they were given digitally animated, interactive work instructions as opposed to paper-based technical drawings. These instructions are able to reduce human errors in ever-changing manufacturing environments faster and, at the same time, reduce the time required to assemble new products or variants. Second, our results show that the advantages of digitally animated, interactive work instructions can best be reaped if provided solely and that combining them with (existing) paper-based technical drawings does not yield any additional benefits. While subjects equipped with both sets of instructions made fewer mistakes than the group with only paper-based technical drawings, they did not need less processing time and did not outperform the group with only digital instructions with regard to any performance measure. This effect may be rooted in the fact that, on the one hand, the digital instruction is a superior means for learning the new task (hence the reduction in defects). But, on the other hand, it consumes additional time to deal with two sets of instructions, which offsets the processing time advantage of the digital instruction over only the paper-based technical drawing. Concluding from this, paper-based technical drawings, which regularly exist on most shop floors, do not complement digitally animated, interactive work instructions. Rather, companies should replace existing paper-based instructions with digital instructions.

Despite their advantageousness, the fact that digital instructions have not yet been widely adopted may be attributed to organizational inertia. As stated in the introduction, research had not yet demonstrated such digital instructions' effectiveness. Traditional quality management systems are usually paper-based, and producing and implementing such digital instructions is difficult and potentially costly (e.g., Yin et al., 2017).

This study has the rare advantage of having taken place in a highly realistic factory setting while being conducted under controlled laboratory conditions. Hence, it achieves high degrees of internal validity and reliability as well as external validity. The focus of this research lies on demonstrating the effectiveness of different forms of work instructions for transferring knowledge to workers who are new to a task.

However, some limitations need to be kept in mind. The essence of the task performed in this experimental study is of limited complexity and future research should verify the results with other manufacturing tasks and in other domains, for example, work preparation and sorting tasks in different industries and health care operations, installation, maintenance, and repair situations as well as disassembly. In addition, possibilities for employee participation in developing digital as opposed to paper-based work instructions

should receive increased attention in future studies. As de Treville et al. (2005) argued, employee participation in the development of instructions positively influences the use of work instruction and intrinsic motivation. As the student sample employed in this study represents an inherent limitation of the generalizability of the results (see Section 3.1), another interesting direction to investigate is how the demographics of workers interact with the effect of digital instructions. Older employees, who are usually not as familiar with digital instructions, might interact differently with the digital tool than younger ones.

Furthermore, digital instructions reduce the amount of paper required on the shop floor and have the potential to increase work place safety by reducing the need for workers to move away from their workstations when looking for instructions. A digital system also enables quick, centralized updates to instructions when changes to the design occur or when flaws are detected. Lastly, digital and interactive tools could provide firms with an edge when recruiting young employees, who are regularly affine to digital media—an important issue in industrialized countries where demographic change and a shortage of skilled labor is apparent (e.g., Letmathe & Schinner, 2017). These other implications of using digitally animated, interactive work instructions on the shop floor should be addressed by future research.

6 | CONCLUSION

Digitally animated, interactive work instructions have clear advantages over traditional paper-based work instructions. With regard to the performance criteria “execution time” and “number of defects,” they lead to significantly better results when learning new tasks. The parallel use of digital and paper-based work instructions cannot be recommended on the basis of the experimental results. Companies should therefore invest more in digital knowledge transfer, while traditional paper-based work instructions should and will be phased out in the future.

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REFERENCES

- Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198.
- Alavi, S., Abd. Wahab, D., Muhamad, N., & Arbab Shirani, B. (2014). Organic structure and organisational learning as the main antecedents of workforce agility. *International Journal of Production Research, 52*(21), 6273–6295.
- Baumers, M., & Holweg, M. (2019). On the economics of additive manufacturing: Experimental findings. *Journal of Operations Management, 65*(8), 794–809.
- Beatty, J. K., Thimling, D., & Walsh, T. (2004, November 16). *Electronic work instruction object oriented system and method. Google Patents*. <https://www.google.com/patents/US6819965>.
- Benkard, C. L. (2000). Learning and forgetting: The dynamics of aircraft production. *American Economic Review, 90*(4), 1034–1054.
- BMBF (Bundesministerium für Bildung und Forschung) (2015). Report on vocational education and training 2015. BMBF. Bonn. https://www.bmbf.de/upload_filestore/pub/Berufsbildungsbericht_2015_eng.pdf
- Clark, J., & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review, 3*(3), 149–210.
- de Treville, S., Antonakis, J., & Edelson, N. M. (2005). Can standard operating procedures be motivating? Reconciling process variability issues and Behavioural outcomes. *Total Quality Management, 16*(2), 231–241.
- Deater-Deckard, K., Petrill, S. A., Thompson, L. A., & Dethorne, L. S. (2005). Fast-track report - a cross-sectional behavioral genetic analysis of task persistence in the transition to middle childhood. *Developmental Science, 3*, 21–26.
- Dong-Sik, J. O., Kim, Y.-W., Yang, U.-Y., & Kim, K.-H. (2012, April 26). *Assembly process visualization apparatus and method. Google Patents*. <https://www.google.com/patents/US20120100520>.
- Euler, D. (1994). (Multi) Mediales Lernen-Theoretische Fundierungen und Forschungsstand. *Unterrichtswissenschaft, 22*(4), 291–311.
- Eysenck, H. J., & Thompson, W. (1966). The effects of distraction on pursuit rotor learning, performance and reminiscence. *British Journal of Psychology, 57*(1–2), 99–106.
- Gilbert, A. (2016). Virtual, augmented and mixed reality. In S. Lackey & R. Shumaker (Eds.), *Virtual, augmented and mixed reality: 8th international conference, VAMR 2016, held as part of HCI international 2016, Toronto, Canada, July 17–22, 2016* (pp. 375–385). Springer.
- Goodell, K. H., Cao, C. G. L., & Schwaitzberg, S. D. (2006). Effects of cognitive distraction on performance of laparoscopic surgical tasks. *Journal of Laparoendoscopic & Advanced Surgical Techniques, 16*(2), 94–98.
- Goss, L. (2001, May 22). *Manufacturing system and method for assembly of computer systems in a build-to-order environment. Google Patents*. <https://www.google.com/patents/US6236901>.
- Grant, A. M. (2008). Does intrinsic motivation fuel the prosocial fire? Motivational synergy in predicting persistence, performance, and productivity. *Journal of Applied Psychology, 93*(1), 48–58.
- Guan, J., Xiang, P., McBride, R., & Bruene, A. (2006). Achievement goals, social goals, and Students' reported persistence and effort

- in high school physical education. *Journal of Teaching in Physical Education*, 25(1), 58–74.
- Holmström, J., Holweg, M., Lawson, B., Pil, F. K., & Wagner, S. M. (2019). The digitalization of operations and supply chain management: Theoretical and methodological implications. *Journal of Operations Management*, 65(8), 728–734.
- Jain, N. K., & Jain, V. K. (2001). Computer aided process planning for agile manufacturing environment. In A. Gunasekaran (Ed.), *Agile manufacturing: The 21st century competitive strategy* (pp. 515–534). Elsevier Science Ltd.
- Kablan, Z., & Erden, M. (2008). Instructional efficiency of integrated and separated text with animated presentations in computer-based science instruction. *Computers in Education*, 51(2), 660–668.
- Kock, N. (2005). Media richness or media naturalness? The evolution of our biological communication apparatus and its influence on our behavior toward E-communication tools. *IEEE Transactions on Professional Communication*, 48(2), 117–130.
- Kock, N. (2009). Information systems theorizing based on evolutionary psychology: An interdisciplinary review and theory integration framework. *MIS Quarterly*, 33(2), 395–418.
- Krauter, L. G., Eide, D. M., & Kersavage, K. K. (2016, December 6). *Apparatus and method for automatic work instruction generation*. Google Patents, <https://www.google.com/patents/US20100175013>.
- Letmathe, P., & Röbler, M. (2016). Spillover effects of learning for production ramp-ups. In *Proceedings of the 3rd international conference on ramp-up Management in Aachen, Germany* (Vol. 51, pp. 111–115). Procedia CIRP.
- Letmathe, P., & Röbler, M. (2019). Tacit knowledge transfer and spillover learning in ramp-ups. *International Journal of Operations & Production Management*, 39(9/10), 1099–1121.
- Letmathe, P., & Schinner, M. (2017). Competence management in the age of cyber physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Industrial internet of things* (pp. 595–614). Springer.
- Letmathe, P., Schweitzer, M., & Zielinski, M. (2012). How to learn new tasks: Shop floor performance effects of knowledge transfer and performance feedback. *Journal of Operations Management*, 30(3), 221–236.
- Letmathe, P., & Zielinski, M. (2016). Determinants of feedback effectiveness in production planning. *International Journal of Operations & Production Management*, 36(7), 825–848.
- Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist*, 32(1), 1–19.
- Mayer, R. E. (2001). *Multimedia learning*. Cambridge University Press.
- Michas, I. C., & Berry, D. C. (2000). Learning a procedural task: Effectiveness of multimedia presentations. *Applied Cognitive Psychology*, 14(6), 555–575.
- Moreno, R., Mayer, R. E., Spires, H. A., & Lester, J. C. (2001). The case for social Agency in Computer-Based Teaching: Do students learn more deeply when they interact with animated pedagogical agents? *Cognition and Instruction*, 19(2), 177–213.
- Nerdel, C. (2002). *Die Wirkung von Animation und Simulation auf das Verständnis von stoffwechselphysiologischen Prozessen*. (Doctoral Dissertation), Christian-Albrechts-Universität zu Kiel.
- Ngu, B. H., Mit, E., Shahbodin, F., & Tuovinen, J. (2009). Chemistry problem solving instruction: A comparison of three computer-based formats for learning from hierarchical network problem representations. *Instructional Science*, 37(1), 21–42.
- Nunnally, J. C., Bernstein, I. H., & ten Berge, J. M. T. (1967). *Psychometric theory* (Vol. 226). McGraw-Hill.
- Paas, F. (1992). Training strategies for attaining transfer of problem solving skill in statistics: A cognitive-load approach. *Journal of Educational Psychology*, 84(4), 429–434.
- Paas, F., Ayres, P., & Pachman, M. (2008). Assessment of cognitive load in multimedia learning. In D. Robinson & G. Schraw (Eds.), *Recent innovations in educational technology that facilitate student learning* (pp. 11–35). Information Age Publishing Inc.
- Paivio, A. (1990). *Mental representations: A dual coding approach*. Oxford University Press.
- Park, O.-C., & Hopkins, R. (1992). Instructional conditions for using dynamic visual displays: A review. *Instructional Science*, 21(6), 427–449.
- Peterson, R. A. (2001). On the use of college students in social science research: Insights from a second-order meta-analysis. *Journal of Consumer Research*, 28(3), 450–461.
- Salomon, G. (1979). *Interaction of media, cognition, and learning: An exploration of how symbolic forms cultivate mental skills and affect knowledge acquisition*. Jossey-Bass Publishers.
- Schnotz, W., Böckheler, J., & Grzondziel, H. (1999). Individual and co-operative learning with interactive animated pictures. *European Journal of Psychology of Education*, 14(2), 245–265.
- Schwan, S., & Riempp, R. (2004). The cognitive benefits of interactive videos: Learning to tie nautical knots. *Learning and Instruction*, 14(3), 293–305.
- Senesac, C. J. (2017, May 3). *Method and apparatus for providing visual assistance in aircraft assembly*. Google Patents. <https://www.google.com/patents/EP2778073A3?cl=en&hl=de>.
- Spangenberg, R. W. (1973). The motion variable in procedural learning. *Audio-Visual Communication Review*, 21(4), 419–436.
- Sun, Z.-Y., Xiao, D.-H., Wang, Y.-J., & Xiao, Y.-L. (2010, April 22). *System and method for directing display of a standard operation procedure of an item using multimedia devices*. Google Patents. <https://www.google.com/patents/US20100100609>.
- Terwiesch, C., & Bohn, R. E. (2001). Learning and process improvement during production ramp-up. *International Journal of Production Economics*, 70(1), 1–19.
- Venkatesan, M. (1967). Laboratory experiments in marketing: The experimenter effect. *Journal of Marketing Research*, 4(2), 142–146.
- Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, 3(4), 122–128.
- Yin, Y., Stecke, K. E., Swink, M., & Kaku, I. (2017). Lessons from seru production on manufacturing competitively in a high cost environment. *Journal of Operations Management*, 49–51, 67–76.
- Yusuf, Y. Y., Sarhadi, M., & Gunasekaran, A. (1999). Agile manufacturing: The drivers, concepts and attributes. *International Journal of Production Economics*, 62, 33–43.

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APPENDIX A: PHOTO OF A FINISHED PENCIL HOLDER



APPENDIX B: INTRODUCTION TO EXPERIMENT (TRANSLATED FROM GERMAN)

Instructions

- Your task is to build 4 units of the pencil holder according to the provided instructions.
- You can find the instructions (Paper Treatment) in the form of paper-based technical drawings of a pencil holder at your workstation/(Digital Treatment) as an interactive work instruction on the screen in front of you/(Both Treatment) in the form of paper-based technical drawings of a pencil holder at your workstation and as an interactive work instruction on the screen in front of you.
- (Paper Treatment) The technical drawings show you the steps for assembling a pencil box/(Digital Treatment) On the screen you can see the individual steps; The screen is a touchscreen on which you can change the viewing angle by dragging; the arrow key in the bottom right corner takes you to the next step and with help of the arrow key in the bottom left corner you can go back to the previous step.
- The goal is to make as few mistakes as possible and to be as quick as possible when assembling each individual pencil box.
- At your workstation, you can find a printout of the payment scheme, which shows you the performance-dependent payment.
- Each pencil box is being evaluated individually and will result in an individual bonus between 0 and 350 ECU.
- In the payment scheme, you can see that you have to focus simultaneously on working quickly and with few errors in order to earn a bonus; it is not sufficient to only excel in one performance dimension while ignoring the other.
- We will shortly distribute the parts and the tools for the first pencil holder.
- As soon as you receive your parts and tools, your individual time will start, which we will measure for you individually.
- When you have finished a pencil holder and would like to hand it in, please raise your hand at your workstation (so that we can see you!).
- We will then immediately stop your time and approach you at your workstation to collect the pencil holder and check it for any defects.
- You will then receive the parts for the next pencil holder and the time will start over at 0 as soon as you have received the parts.
- After you have finished and handed in four pencil holders, you will receive a questionnaire which we would like you to fill out completely at your workstation.
- After filling out the complete questionnaire, please raise your hand again. We will then guide you to the front desk where you will receive your payment based on the performance with regard to all four pencil holders
- The minimal payment is 500 ECU, which equals €5, the maximal payment is 1900 ECU, which equals €19.
- We will now distribute parts and tools.

APPENDIX C: POST-EXPERIMENTAL QUESTIONNAIRE AND SUPPLEMENTARY ANALYSIS

Panel C1: Post-experimental questionnaire (translated from German)

Session:

1. Please indicate the number of your workstation:

2. To understand the work instructions and fulfilling the task, I invested ... mental effort.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
very low	low	rather low	neither low nor high	rather high	high	very high

Please indicate to what extent you agree with the following statements whereby 1 means “strongly disagree” and 7 means “strongly agree.”

3. My experience with technical drawings *before the experiment* was more extensive compared with that of my fellow students.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

4. My experience with digital work instructions *before the experiment* was more extensive compared with that of my fellow students.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

5. My craft skills *before the experiment* were more pronounced compared with those of my fellow students.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

6. My technological understanding *before the experiment* was more pronounced compared with that of my fellow students.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

7. Why were you motivated to fulfill the task as well as possible?
... Because I enjoyed the task itself.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

... Because it was fun.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

... Because I found the task engaging.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

... Because I enjoyed it.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

8. Regardless of whether or not I liked the task, I worked my hardest to complete it.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

9. Regardless of whether or not I found the task boring, I tried to learn and do well.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

10. Regardless of whether or not I liked the task, I wanted to finish it.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

11. Regardless of whether or not I found the task boring, I wanted to finish it.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

12. The instructions helped me to understand the task.

1	2	3	4	5	6	7
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
strongly disagree						strongly agree

13. Please indicate your program of study (Bachelors/Masters etc. and program):**14. Please indicate how many semesters you have studied so far (in total, not only in your current program of study):****15. Please indicate your age:****16. Please indicate your gender:**

female male

Panel C2: Supplementary analyses

The post-experimental questionnaire allows additional variables to be analyzed. First, mental effort was collected by a single-item asking the subject to rate the mental effort employed in order to understand the instructions and the task from “very little” to “very much” on a 7-point scale. The scale was adapted from Paas (1992) and Paas et al. (2008). Second, intrinsic motivation was inquired through a four-item scale taken from Grant (2008) where subjects expressed agreement with different statements about motivational reasons to perform well in the task on a seven-point Likert scale. Cronbach's alpha for the scale equaled .90 well above recommended cut-off levels of 0.70 (Nunnally et al., 1967) and hence implies reliability. All principal components load with values higher than 0.4 and the Kaiser-Meyer-Olkin criterion equals 0.79, well above the recommended cut-off level of 0.5. Third, goal commitment or persistence was also measured with a four-item scale adapted from Guan et al. (2006) and Deater-Deckard et al. (2005). Again, subjects expressed their agreement with different statements on a seven-point Likert scale. Cronbach's alpha equaled .85. All principal components load with values higher than 0.4 and the Kaiser-Meyer-Olkin criterion equals 0.60. Fourth, helpfulness of the instructions for understanding the task was measured with a single-item scale where subjects rated on a seven-point Likert scale to what extent they agree with the statement that the instructions helped them in understanding the task (Moreno et al., 2001).

As control variables, subjects indicated their age, gender, program of study—which was the basis for the assessment of whether they are in a technical program or not—and semesters studied. In addition, subject assessed their prior experience as it was before the start of the

experiment with regard to technical drawings or digital instructions, respectively, and a self-assessment of their craftsmanship and technological understanding (Letmathe et al., 2012). The items were also measured with a seven-point Likert scale. For each inquired skill, participants indicated the extent to which they agree with the statement that their knowledge or skill is superior to that of the average student (Letmathe & Röbler, 2019).

On the basis of these variables, we performed supplementary analyses to investigate the influence of the additional variables on the results. When looking at the coefficients of the collected control variables, we noticed that especially the self-reported craftsmanship and, in most cases, the self-reported technological understanding has a positive and significant influence on the performance with regard to quality and time. This hints at the fact that the subjects' self-assessment of their previous knowledge and skills was fairly accurate. In the same way, the number of semesters studied improves the performance regarding both performance metrics. Apparently, the academic education has a positive side-effect on students' abilities also with regard to this manufacturing task. Although the effect of academic education is certainly not at the center of this paper it should receive further attention in future studies.

Moreover, we conducted supplementary analyses with regard to the effect of the variables collected through a post-experimental questionnaire reflecting the subjects' self-reported perceptions of the respective measures. OLS regressions of each of the dependent variables on the respective treatment dummy did not yield significant results for any of the variables and any of the treatments, regardless of the inclusion of control variables.

APPENDIX D: PAYMENT SCHEME (TRANSLATED FROM GERMAN)

Payment Scheme

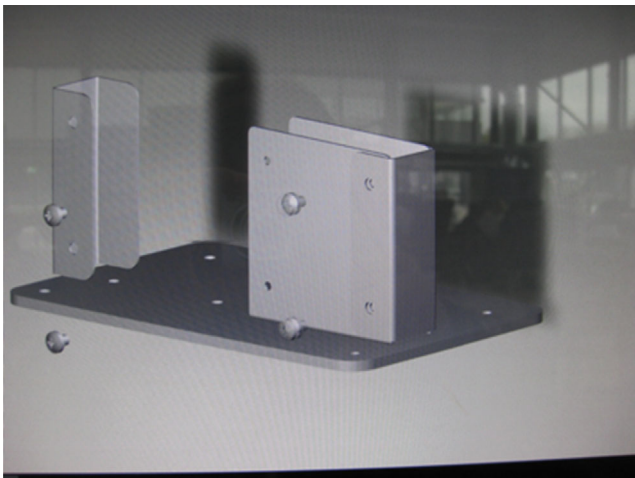
Basic Payment (in ECU)	= 500
Performance bonus per pencil holder (in ECU)	dependent on individual performance (see table below)
Number of pencil holders	= 4
Total payment	= basic payment + performance bonus of the 4 pencil holders
Minimal total payment (in ECU)	500
Maximal total payment (in ECU)	1900
100 ECU \square 1 €	

Calculation of performance bonus per pencil holder (in ECU)

Defects (Number of)	Required Time (Minutes)							
	$\leq 3:00$	$\leq 4:00$	$\leq 5:00$	$\leq 6:00$	$\leq 7:00$	$\leq 8:00$	$\leq 9:00$	$> 9:00$
0	350	300	250	200	150	100	50	0
1	280	240	200	160	120	80	40	0
2	210	180	150	120	90	60	30	0
3	140	120	100	80	60	40	20	0
4	70	60	50	40	30	20	10	0
> 4	0	0	0	0	0	0	0	0

APPENDIX E: PHOTOS OF INSTRUCTIONS

Example of digitally animated, interactive work instructions:



Example of paper-based technical drawings:

