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Make complex assembly work more accessible through projection-based work instructions

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Abstract

Purpose – Labor market shortages are making it increasingly difficult for organizations to find skilled workers. As a result, there is growing demand for technologies that either automate tasks or reduce the skill level required to perform them. This randomized controlled experiment examines whether assistive technology – specifically, projection-based work instructions – can enable individuals with lower educational levels to successfully perform tasks that typically require higher educational levels.

Design/methodology/approach – We conducted a field experiment involving 80 students enrolled in technical vocational programs. Participants were asked to assemble a car battery and were randomly assigned within their educational level (lower vs higher) to receive either paper-based or digital work instructions. Task performance was evaluated based on completion time, number of errors and help requests.

Findings – Participants using digital work instructions completed the task significantly faster than those using paper-based work instructions, regardless of their educational level. They also made fewer errors and requested less help. While participants with higher education levels generally performed the task quicker, lower-educated participants using digital work instructions matched the performance of higher-educated participants using paper-based work instructions.

Originality/value – This randomized controlled experiment demonstrates that assistive technology can enhance task performance to the extent that individuals with lower education can achieve results comparable to peers with higher education. These findings suggest that such technology not only improves worker productivity but also expands the available talent pool for organizations struggling with labor shortages. Future research should explore how assistive technology can support long-term skill development and employee learning.

Keywords Human resources in manufacturing – workforce,
Manufacturing technology and innovation – product – process or technological innovation,
Type of industry – motor vehicle industry, Type of manufacturing process – assembly lines,
Data collection method – action research,
Data collection method – survey (in-person interviews and written questionnaires)

Paper type Research article

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Quick value overview

Interesting because: Manufacturing organizations increasingly struggle with labor shortages while assembly processes become more complex. This study examines whether assistive technology (i.e. projection-based digital work instructions) can make complex assembly tasks that typically require higher educational levels accessible to workers with lower educational levels. Unlike prior studies that mainly examined general productivity effects of such digital work instructions, this randomized controlled experiment specifically investigates whether assistive technology can reduce education-related performance differences in a realistic manufacturing environment.

Theoretical value: The study demonstrates that the relationship between educational level and task performance is moderated by assistive technology. Higher-educated participants generally completed tasks faster, made fewer errors and required less supervisory support. However, digital work instructions significantly improved productivity, quality and independence across both educational groups. Most importantly, lower-educated participants using digital work instructions achieved task completion times equivalent to higher-educated participants using paper-based work instructions, while also showing comparable error rates and help requests (Figure 1). These findings extend prior research that largely treats workers as a homogeneous user group and provide empirical evidence that digital work instructions can reduce education-related performance gaps in complex assembly work.

Practical value: For manufacturers, the findings show that assistive technology can broaden the pool of workers able to perform complex assembly tasks without reducing productivity or quality. Digital work instructions improved task completion times by 16–20%, reduced errors by 46–60% and lowered help requests by 69–83%. Managers can use such systems to reduce onboarding time, decrease supervisory support requirements and improve operational flexibility in tight labor markets. The results further suggest that digital work instructions can support the upskilling of unqualified workers while simultaneously improving the performance of already qualified workers.

1. Introduction

Across the European Union, labor shortages are becoming increasingly acute, particularly in sectors such as manufacturing and construction. These shortages stem from structural demographic shifts: while the number of available jobs continues to grow, the working-age population is shrinking (Eurofound, 2024a). The Netherlands exemplifies this trend, with

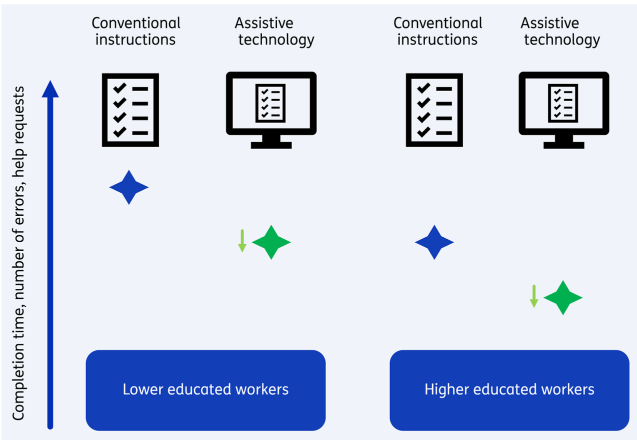

Figure 1. Assistive technology reduces education-related performance gaps in complex assembly tasks. Note. This figure is a simplified version of Figure 8. For quantification and statistics, refer to figure8

more vacancies than unemployed individuals (CBS, 2024). As a result, organizations face increasing pressure to sustain productivity despite a limited workforce.

At the same time, the nature of work itself is changing. Rapid technological developments and evolving work environments have created a continuous need for training, as reported by a large-scale survey of 4,461 Dutch companies (Hulsegge *et al.*, 2021). Work processes are becoming more complex, dynamic and information-rich, exposing workers to cognitive overload and higher demands for adaptability (Hulsegge *et al.*, 2021; Johansson *et al.*, 2017; Leder *et al.*, 2022). Yet, despite high vacancy levels, many young workers and those with lower educational attainment remain underrepresented in employment. Persistent skills mismatches and insecure job conditions prevent these groups from fully participating in the labor market (Eurofound, 2024b; European Commission, 2023). This tension between growing complexity and persistent labor shortages is particularly evident in manufacturing, where companies must remain flexible in response to high-mix, low-volume production demands (Kocsi *et al.*, 2020; Srivastava and Bag, 2023).

Against this backdrop, attracting and retaining sufficiently skilled workers remains a major challenge. One potential avenue to address this issue lies in leveraging assistive technologies — specifically, digital work instructions— to make complex manufacturing tasks more accessible to individuals with lower levels of education. By supporting workers' understanding and execution of intricate processes, such technologies may help ease labor market pressures and broaden the pool of employable talent.

Digital work instructions combine step-by-step visualization with a short text. The sequential nature of digital work instructions can transform a more complex task into a series of clearly defined subtasks, which is better aligned with the training of workers with lower educational levels (Clark and Paivio, 1991; Kock, 2005, 2009; Mayer, 1997, 2009; Paivio, 1990; Wickens, 2008). Therefore, digital work instructions can be useful when workers face new or more complex tasks, or have to adapt to changes in the process or variations in the product (Letmathe and Rößler, 2021).

1.1 Features and known effects of digital work instructions

Traditional work instructions are typically provided on paper or displayed digitally on monitors near the workstation. These formats often require workers to identify, interpret, and plan the relevant steps themselves and may not present information in a step-by-step manner. In addition, feedback such as measurements or production notes is frequently recorded offline or manually. Such characteristics can increase perceived task complexity, elevate cognitive load, and reduce productivity while increasing the likelihood of errors during task execution (Eesee *et al.*, 2025).

Digital work instructions have emerged as a way to address these limitations and offer additional benefits. While there is a wide variety of digital work instruction systems, they all share the core feature of delivering dosed, just-in-time and step-by-step instructions, thereby improving the timing, clarity and contextual relevance of the information provided (Leder *et al.*, 2022). By structuring tasks into sequential subtasks and embedding relevant information at the point of use, digital work instructions can reduce unnecessary information processing demands and support procedural understanding. This is particularly relevant in assembly environments characterized by high variability and increasing task complexity, where workers must continuously adapt to product changes and dynamic workflows.

The main differences between digital work instruction systems lie in their modes of visualization, which can be tailored to the task type, user profile and working environment. Formats range from simple text and image displays on monitors or smart glasses to more immersive solutions such as 3D animations on augmented reality (AR) headsets and spatial projections directly onto the work surface (Leder *et al.*, 2022).

Research shows that digital work instructions can significantly enhance training and performance outcomes. Video-based work instructions, for example, have been linked to reduced training time and increased productivity (Agarwal and Bhandari, 2023). Animated work instructions have similarly been shown to decrease task completion time and reduce errors compared to paper-based work instructions (Letmathe and Rößler, 2021). These findings are consistent with broader research on assembly complexity and cognitive load, which indicates that structuring information and reducing search and planning requirements can mitigate negative performance effects associated with complex manual and human–robot collaborative assembly processes (also see Capponi *et al.*, 2025).

A key factor underlying these benefits is the proximity and integration of information within the user's workspace. When instructions are delivered through mobile displays or head-mounted displays (HMDs), guidance remains within the worker's immediate field of view, minimizing the need for visual shifts between the task and reference material. More advanced digital work instructions solutions use spatial AR, where instructions are projected directly onto work surfaces via projectors or AR headsets. By embedding information directly in the context of action, these technologies can reduce task complexity, support procedural understanding, and lower the skill threshold — thereby narrowing the performance gap between novices and experts, although they may introduce some additional cognitive load (Bal *et al.*, 2020).

Research on complex assembly processes indicates that production quality can be improved through human–robot collaboration, potentially due to the reduction or elimination of manual part-selection tasks (Verna *et al.*, 2023). Similarly, part-selection performance may be further improved by integrating digital work instructions with spatial AR. For example, spatial AR can visually highlight the containers that hold the required components, thereby reducing search time and selection errors. Spatial AR has, in general, been shown to enhance task performance and assembly quality more effectively than traditional screen-based digital work instructions, with these advantages becoming particularly pronounced in complex tasks (Bosch *et al.*, 2017; Funk *et al.* Oct 26, 2015). It has also shown potential to support inexperienced users or individuals with mild disabilities (Bosch *et al.*, 2020; Funk *et al.* Oct 26, 2015). Both AR HMDs and projection-based systems have been associated with faster task execution and fewer errors compared to paper-based work instructions, across user groups including students and professional operators (Kolla *et al.*, 2021). In addition, "pick-to-light" and "pick-to-projector" systems used to indicate where to retrieve or place parts can further streamline tasks (Bosch *et al.*, 2017). These systems can be integrated into AR workflows, with features like automatic instruction advancement based on motion detection or object recognition.

1.2 Research gap

Although prior research consistently demonstrates that digital work instructions enhance task performance, reduce errors and support novices across various manufacturing settings (Bosch *et al.*, 2020; Couckuyt *et al.*, 2024), existing studies largely treat users as a homogeneous group and therefore provide limited insight into how these benefits vary between workers with different educational backgrounds (Mark *et al.*, 2021).

This omission is notable in light of research on assembly complexity and cognitive load, which suggests that individual differences in prior knowledge, training level and experience substantially shape how task demands are perceived and managed. Recent reviews explicitly highlight the absence of empirical research examining differential effects across user groups (Mark *et al.*, 2021; Nijland *et al.*, 2025). Consequently, it remains unclear whether digital work instructions merely improve performance in general or whether they can specifically compensate for differences in formal training and educational attainment.

Specifically, no experimental studies have investigated whether digital work instructions can enable workers with lower vocational training levels to perform tasks typically requiring higher levels of educational attainment. This lack of evidence is particularly salient in light of persistent labor shortages and skills mismatches, which amplify the need for solutions that could lower skill thresholds and expand the pool of employable workers. Addressing this gap is necessary to substantiate claims about the potential of digital work instructions to broaden access to complex manufacturing tasks rather than only optimizing performance within already skilled populations.

1.3 Main research question

This study addresses the identified gap by examining whether tasks typically suited for vocationally trained workers with relatively higher educational levels (here: Dutch MBO4-level (Ministry of Education Culture and Science n.d.)) can be made accessible to vocationally trained workers with relatively lower educational levels (here: Dutch MBO2-level (Ministry of Education Culture and Science n.d.)) through the use of digital work instructions.

More specifically, we examine whether digital work instructions can reduce performance differences associated with educational level in a complex assembly context. In other words, can digital work instructions support the "upskilling" of lower-educated workers (i.e. MBO2) to a performance level comparable to that of higher-educated workers (i.e. MBO4) using conventional paper-based work instructions?

Based on the literature discussed above, and particularly on findings suggesting that digital work instructions can reduce task complexity and support novices, we hypothesize that digital work instructions can indeed enable lower-educated workers to perform such tasks with similar levels of productivity, product quality and independence as higher-educated workers using paper-based work instructions.

1.4 Outline

The remainder of this paper is structured as follows. Section 2 describes the methodology, including participant recruitment, experimental design and measurement procedures. Section 3 presents the results of the randomized controlled experiment on task performance, error rates and independence. Section 4 discusses the findings in relation to existing research on digital work instructions, outlines practical and theoretical implications, and highlights limitations. Finally, Section 5 concludes the paper and offers directions for future research.

2. Method

2.1 Participants

Participants were recruited from VISTA College, a school located near the experimental site, using flyers and word-of-mouth recommendations. Participants were included based on two key criteria: they had to be enrolled in a technical education program and capable of performing assembly work, while not having prior familiarity with the specific procedures used in the study. The required number of participants was determined through power analysis based on results from a previous pilot experiment employing similar outcome measures in a within-subjects design (Stroosma, 2022). Participants were informed about the voluntary nature of their participation, assured of their right to withdraw at any time, and provided written informed consent, in accordance and as approved by the ethics committee of [anonymized organization]. Furthermore, participants were compensated with a €25 voucher for their time.

When referring to lower educational levels in this article, we refer to the difference between the secondary vocational education level 2 (MBO2) and level 4 (MBO4). In the Dutch education system, these levels differ in several aspects, of which three differences are most prominent (Kollöffel and De Jong, 2013; Ministry of Education Culture and Science n.d.; Rijksoverheid, 2024; VISTA college, 2024a, b). The first difference is that MBO2 workers are trained to perform one relatively simple task, while MBO4 workers can perform more complex tasks. The second difference is that MBO2 workers are supposed to work under supervision, while MBO4 workers are allowed to supervise and coordinate others. Finally, the MBO2 education takes 1–2 years, while the MBO4 education takes 3–4 years. Typically, complex manufacturing processes in high-tech industries require MBO4 work and reasoning skills. This study included 80 participants, of which 50% lower-educated (MBO2) students and 50% higher-educated (MBO4) students. The majority of participants were male (99%) and ranged in age from 16 to 28 years (*Mean* = 19.3; *Standard Deviation* = 1.9).

Prior to analysis, we assessed for both educational levels whether the students in the paper and digital conditions were equally distributed in terms of self-efficacy and reading ability. We examined whether the data followed a normal distribution and whether the variance of the data was approximately equal across all groups being compared. This was to ensure that despite random allocation to intervention groups, any observed effects between the paper and digital conditions could not be attributed to pre-existing differences. Reading ability was included because it influences how well participants interpret instructions, and self-efficacy because it affects self-confidence and task performance. An independent *t*-test was used to compare reading ability (continuous data type), while a Mann–Whitney U test was performed for self-efficacy (ordinal data type). Results showed that there were no significant differences between the group that received paper-based work instructions and the group that received digital work instructions, for both lower educational (MBO2) level (reading ability: $t(38) = 0.018$, $p = 0.986$, self-efficacy: $U = 192.000$, $p = 0.828$) and higher educational (MBO4) level (reading ability: $t(38) = 0.654$, $p = 0.517$, self-efficacy: $U = 189.500$, $p = 0.775$). This means that the groups of students were homogeneous in terms of reading ability and self-efficacy.

2.2 Study design

A between-subject design was used to investigate the effectiveness of digital work instructions in making work more accessible during the assembly of a battery pack for a hybrid electric vehicle. Participants were assigned to either the intervention group or the control group through balanced randomization (Table 1). The intervention group received digital work instructions, while the control group received paper-based work instructions. The study was conducted over eight working days (from May 27 to June 6 2024) and was approved by the [anonymized organization] ethics committee.

2.3 Experimental setting

The experiment took place in the research and development production line for automated battery pack assembly at VDL Nedcar in Born (the Netherlands). This production line was constructed under the Green Transport Delta–Electrification (GTD-E) project and consists of several advanced manual and automated workstations designed for high-mix, low-volume battery pack production. The experimental task involved manually assembling a battery pack for a BMW Mini plug-in hybrid electric vehicle. This pack includes multiple battery modules, wiring, a controller and a cooling system within an aluminum housing. The assembly task consists of a high variety of activities, including screwing, connecting cables, installing support clips, and pick-and-place operations. This high variety, including some other aspects like high voltage safety, makes the manufacturing process complex such that workers should be qualified at the higher educational (MBO4) level for real production.

A selection of tasks had to be made since the complete assembly encompasses approximately 80 steps, taking an experienced worker about 30 minutes to complete. However, for inexperienced participants, it does take a lot longer. Therefore, we shortened the

Table 1. Balanced randomization of the groups*

	Lower educational level (MBO2)	Higher educational level (MBO4)
Digital work instructions	20 students	20 students
Paper-based work instructions	20 students	20 students

Source(s): Authors’ own work

task by selecting the most interesting activities with minimal repetition. We also minimized tasks such as screwing bolts, which are time-consuming but requires little information transfer from the instruction. The final procedure consisted of 36 steps, including 13 picking actions, creating a task that would take less than 30 minutes for lower-educated (MBO2) participants using paper-based work instructions. This was based on a pilot preceding the actual experiment. For safety reasons, the actual battery modules were replaced with identical but empty shells due to their weight and high voltage.

2.3.1 Workstations. Participants from the intervention and the control group worked in parallel on the same assembly task at their own workstation. Both workstations consisted of an assembly table on which the lower half of the aluminum housing of the battery pack was placed, providing the basis for the assembly task. The assembly table also contained a torque-controlled screwdriver (Cleco) and three labelled trays. The trays each held a different screwdriver bit, which was needed to complete the tasks. Additionally, at both workstations, a cart with materials was positioned a few meters to the right, at exactly the same distance from the assembly table for both conditions. The cart contained all of the components required to complete the 36 assembly steps. All components and bolts were given unique identification numbers. Accordingly, each tray in the material cart was labeled with a corresponding identification number.

The key difference between the workstations is that the intervention station was equipped with an Ansomatic (Ansomat, Belgium) set-up. At this workstation, a monitor was placed behind the assembly table to present the digital work instructions to the participants. Additionally, regions of interest were indicated on the assembly table by means of AR projections from above. Next to the assembly table, there was a device with clickable buttons (stream deck) which was connected to Ansomatic and could be used to trigger the next step. Furthermore, the torque-controlled screwdriver for this workstation was connected to Ansomatic as well, to automatically proceed to the next step when the right torque was achieved. The pick-to-light beamer system consisted of Ansomatic projecting a light on the place from which to pick a part, combined with a proximity sensor (IFM), to detect whether the operator had reached into this place. A schematic of the projected digital work instructions flow is shown in Figure 2. To the contrary, the control group did not have these features on their

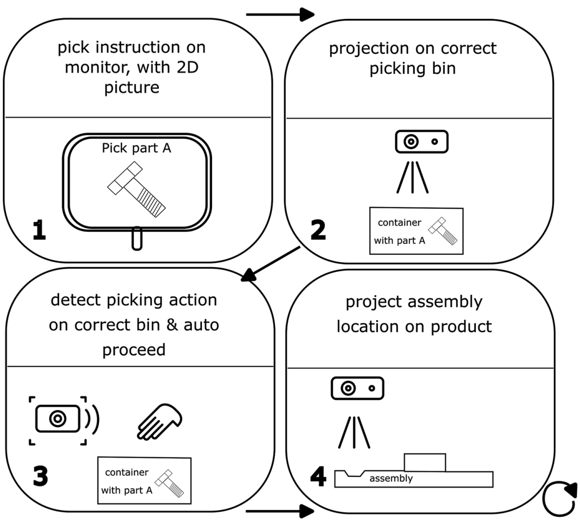

Figure 2. A generalized schematic of the projected digital work instructions flow. 1) Starting with an instruction text with a visualization on a monitor. Followed by 2) green light projections on the correct picking bin, 3) detection of a picking action in the correct bin, automatically triggering 4) the assembly step with the location projected on the assembly. Source: Authors' own work

workstation. For them, the work instructions were printed out on A3 paper sheets and placed on the adjacent table. Both set-ups are shown in Figure 3.

2.3.2 Work instructions. The 36 assembly steps were converted into work instructions and then programmed as digital work instructions in Ansomat. Each step in the digital work instructions consisted of textual and visual instructions (Figure 4). The textual instructions were written in simple, clear Dutch, beginning with an active verb followed by the subject and occasionally some extra information. To easily translate visual information from the instruction to the real product, we used photos of the actual product instead of schematics or drawings. In addition, pick-to-light projections and pick detections were programmed, which highlighted areas of interest on both the material cart and the aluminum housing of the battery pack, depending on the active step (Figure 5).

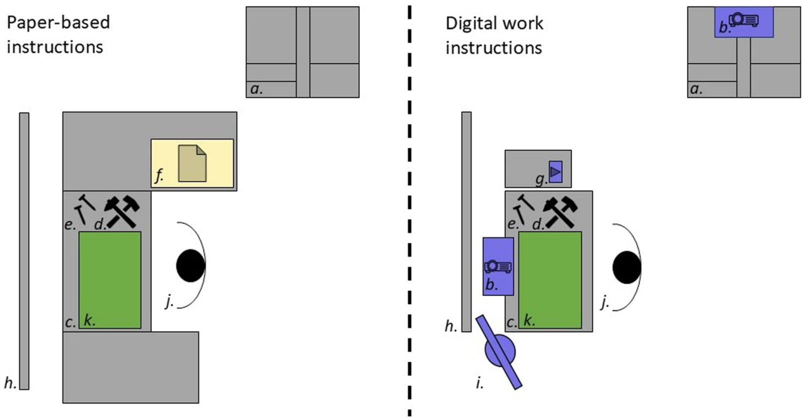

Figure 3. The set-up of the paper-based workstation (left) and the digital workstation (right). The (j) operator is visualized in both workstations. The workstations consist of (a) a material cart, (c) an assembly table, (d) the Cleco screwdriver, (e) screwdriver bits, (h) a workstation shield and (k) the assembly product. The paper-based workstation differentiates through the use of (f) paper-based work instructions, whereas the digital workstation contains two (b) pick-to-light beamers, (g) a stream deck and (i) a monitor with digital work instructions. Source: Authors' own work

Figure 4. Example of digital work instructions. Translation: insert connector 18 into the battery housing and tighten the screw slightly by hand. Note: keep the connector wire facing you and do not tighten the screw all the way. Source: Authors' own work

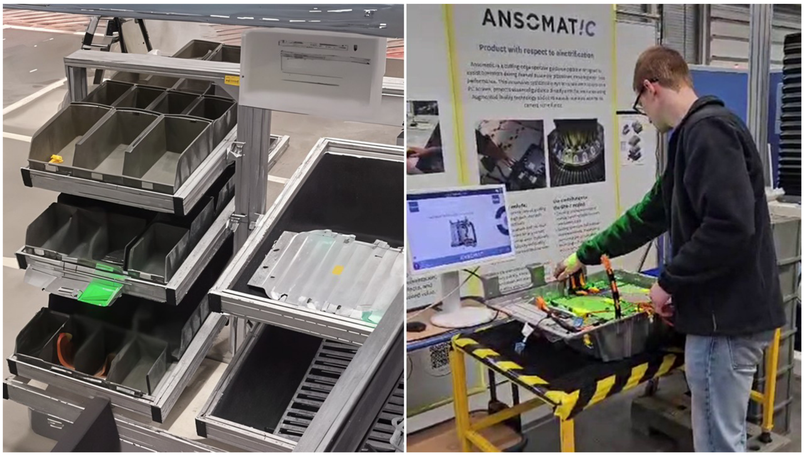

Figure 5. Pick-to-light projections of digital work instructions on the materials cart and on the assembly table. Source: Authors' own work

For the paper-based work instructions, the texts were identical to the digital work instructions. The images were mostly the same, some additional annotations were added to account for the information contained in the projections in the digital work instructions condition. The 36 steps were systematically organized into coherent sections and documented across eight pages. The format and layout of the paper-based work instructions were adapted from VDL Nedcar common practices for the GTD-E production line and shown in Figure 6. It consists of a format with a main title, a subtitle and three columns of information. The central

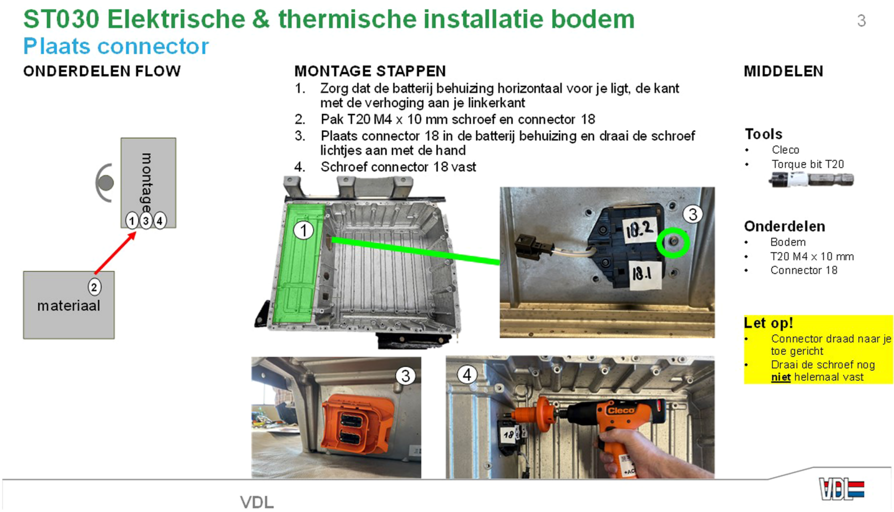

Figure 6. Example of paper-based work instructions. Translation: 1. Make sure the battery housing is horizontal in front of you, the side with the elevation on your left; 2. Take screw T20 M4x10mm and connector 18; 3. Place connector 18 in the battery housing and tighten the screw slightly by hand; 4. Screw connector 18 tight. Note: keep the connector wire facing you and do not tighten the screw all the way. Source: Authors' own work

column contains the written assembly instruction on top and the images below. The numbering on the images followed the step numbering. The left column contains a schematic flow of the parts with step numbers indicating where the part should be collected/used. The right column indicated the means to perform the task, like the tools and bits, the parts by name and an attention area to alert the operator (if any).

2.4 Experimental procedure

After arriving at the experimental site, participants first attended a presentation where they received information about the experiment. They also received general assembly instructions, including how to use cable clamps, connectors and the Cleco screwdriver. Before participants could begin the assembly task, they were required to complete a self-efficacy questionnaire. Participants were then given an explanation of the workstation where the assembly task would take place. They were directed to the location of the work instructions, battery components and tools that could be used. Participants in the intervention group were given additional instructions on progressing through the assembly steps and the additional guidance via the pick-to-light projections. Subsequently, a timer was set and participants had 30 minutes to complete the assembly task. If they were not able to finish the complete task, their last step was noted and the assembly was stopped. After the assembly task, participants completed the technology acceptance model (TAM) questionnaire, followed by a reading test to assess reading speed. After completion, participants were instructed not to share details of the experiment with others who had not yet completed the task.

2.5 Measurements

Self-efficacy. To assess participants' general beliefs regarding their ability to successfully perform work tasks, an adapted version of the self-efficacy questionnaire was administered (Lagerveld *et al.*, 2010). The questionnaire consisted of eleven items that had to be answered on a scale of 1 = not agree to 5 = totally agree (Lagerveld *et al.*, 2010). Two examples are "I can do my work well" and "If something goes wrong while I work, I can deal with it." For the analysis, the average of these items was taken. The internal consistency as measured by *Cronbach's alpha* was 0.83. Self-efficacy was measured to validate that the digital work instructions and paper instructions groups were equally distributed.

Reading ability. In order to get an impression of the reading skills of the participants, an adapted version of the 3-min reading test was used (van Til *et al.*, 2018). The test consists of three reading cards with 150 easy, average or more complex words. Since the reading test is actually for primary education, we have chosen to only use the third reading card in this study. After the instructions of the experimental leader, the participants were asked to read the words out loud one by one. They were given one minute to do this. The experimental leader kept a score sheet to keep track of how many words were read in the allotted time and how many reading errors were made. Subsequently, the number of words that were read out correctly was calculated. Reading ability was measured to validate that the digital work instructions and paper instructions groups were equally distributed.

Performance. Performance was measured using three different constructs. The first construct is *task completion* time, which corresponds to the *productivity* of the participant (Bosch *et al.*, 2017, 2020). It is measured as the time it took the participant from the moment he or she started reading the first instruction until the moment the last part was assembled, or the 30 minutes that had passed since the start if they did not complete the task. In the latter case, the last completed subtask was noted.

The second construct is the *total number of errors*, which corresponds to the *quality* the participant achieved during the task (Bosch *et al.*, 2017, 2020; Letmathe *et al.*, 2012). Errors were counted by the experimental leader on the notation sheet when the error was not directly recovered or when there was an immediate risk of damage or safety. The experimental leaders were instructed not to point out errors to the participant unless a certain future step would become impossible or recovery would become too time-consuming. To guide the experimental leaders, failure modes were predefined for all steps.

The third construct is the *total number of help requests* made by the participants, which we consider as a measure of their *independence* during the task. Participants were allowed to ask for guidance about the instructions in case they felt the need to do so. All types of supervisory support were marked, whether this was a confirmation on doing the right thing or a question on how to interpret or do a specific step. Additionally, when participants clearly had difficulty understanding the step at hand, the experimental leader was allowed to intervene and guide the participant.

Technology acceptance model. To gain insight into the acceptance of either the paper-based work instructions or digital work instructions, we administered a questionnaire composed of selected questions from the TAM (Venkatesh and Davis, 2000; Venkatesh and Bala, 2008). The constructs included in the study were: perceived usefulness (PU), perceived ease of use (PEOU) and a single question from enjoyment (ENJ): – "I find using the system to be enjoyable," behavioral Intention (BI) – "I presently intend to use the system regularly at work" and computer self-efficacy (CSE) – "I could complete the job using the system if there was no one around to tell me what to do as I go." The internal consistency of the multiple-question constructs was validated using Cronbach's alpha: PU (7 items, *Cronbach's alpha* = 0.87) and PEOU (6 items, *Cronbach's alpha* = 0.86).

2.6 Data analysis

Normality could be assumed for task completion time, hence parametric statistics were used. The effect of instruction type and educational level on task completion time was evaluated using a two-way Analysis of Variance (ANOVA) in SPSS. To test equality between higher-educated (MBO4) students using paper-based work instructions and lower-educated (MBO2) students using digital work instructions, a TOST was performed in R, using a margin of equivalence of 5% (Richter and Richter, 2002; Schuirmann, 1981).

For the number of errors, the number of help requests and technology acceptance measures, normality could not be assumed. To test for multiple factors – education level and type of instructions – with possible interaction effects, a transformation was done, since nonparametric tests are not capable (Wobbrock *et al.*, 2011). Therefore, we used the aligned ranked transformation before conducting ANOVA tests (Wobbrock *et al.*, 2011). Additionally, our main research question is related to equivalence of lower-educated (MBO2) workers using digital work instructions compared to higher-educated (MBO4) workers using paper-based work instructions. TOST is not suited for nonparametric results. Therefore, for the number of errors as well as the number of help requests, a planned contrast was conducted, using Mann–Whitney U tests in SPSS. Figure 7 depicts all the steps of the applied methodology and statistical analysis.

3. Results

The effects of educational level and type of instructions on task time, number of errors and number of help requests are visualized in Figure 8. For all three outcome variables, we found significant main effects for both educational level and instruction type, which are further explained below.

3.1 Task completion time

A significant main effect of both educational level ($F(1) = 17.282$, $p < 0.001$) and type of instruction ($F(1) = 14.144$, $p < 0.001$) on task completion time was found. The main effect of educational level indicates that, as hypothesized, in general, higher-educated (MBO4) students were faster than lower-educated (MBO2) students. The main effect of instruction type indicates that lower-educated (MBO2) and higher-educated (MBO4) students were

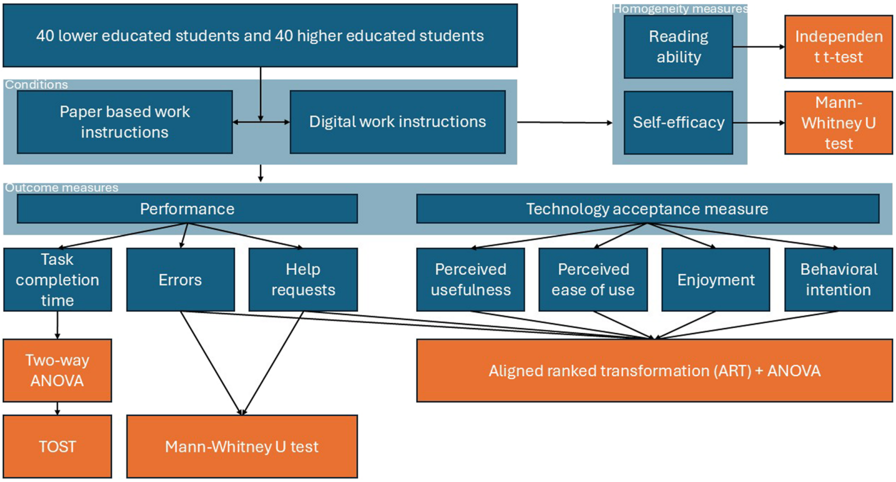

Figure 7. Flow diagram of the research design, measurements and statistical analyses. Source: Authors' own work

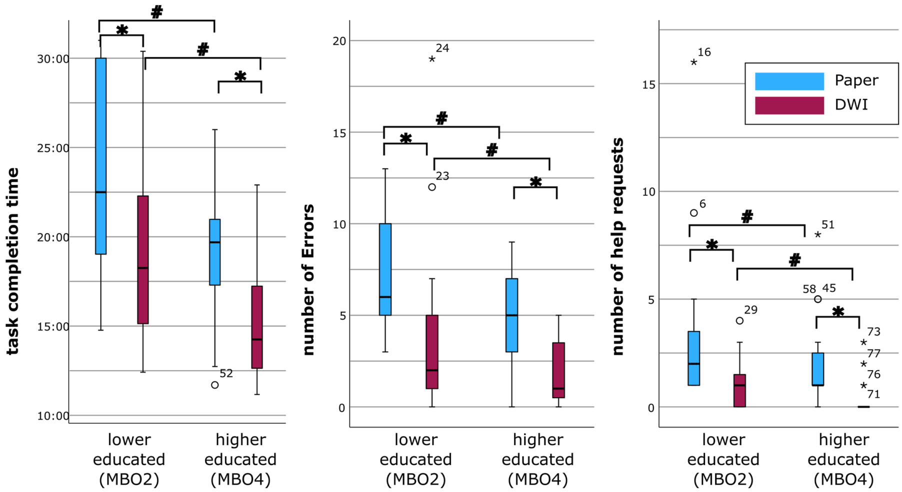

Figure 8. Effects of instruction type and educational level on execution time, number of errors and help requests. Significant effects of instruction type are indicated with *, effects of educational level with #. Source: Authors' own work

significantly faster in conducting the assembly task while receiving digital work instructions as opposed to paper-based work instructions. The interaction effect was not significant ($F(1) = 0.002$, $p = 0.965$), meaning that both lower-educated (MBO2) and higher-educated (MBO4) students benefited equally from digital work instructions.

The TOST test, which was conducted to test equality between higher-educated (MBO4) students using paper-based work instructions and lower-educated (MBO2) using digital work instructions was significant, indicating that the two can be considered as equal, when allowing for a 5% difference ($t(38) = 2.758$, $p = 0.004$). Moreover, although not significantly different, Figure 8 shows that the median time to finish for lower-educated (MBO2) students with digital work instructions is slightly below that of higher-educated (MBO4) students with paper-based work instructions. This suggests that, had equality not been established, any observed difference would have been attributable to the slightly shorter task completion time of lower-educated (MBO2) students using digital work instructions compared to higher-educated (MBO4) students using paper-based work instructions.

3.2 Number of errors

A significant main effect of both educational level ($F(1) = 8.185$, $p = 0.005$) and type of instruction ($F(1) = 32.612$, $p < 0.001$) on the number of errors was found. The main effect of educational level indicates that, as hypothesized, in general, higher-educated (MBO4) students made fewer errors than lower-educated (MBO2) students. The main effect of instruction type indicates that lower-educated (MBO2) and higher-educated (MBO4) students made significantly less errors, during the assembly task, while receiving digital work instructions as opposed to paper-based work instructions. The interaction effect was not significant ($F(1) = 0.806$, $p = 0.372$), meaning that, with regard to the number of errors, both lower-educated (MBO2) and higher-educated (MBO4) students benefited equally from digital work instructions.

From Figure 8, it can be seen that all quartiles for the number of errors are slightly lower for lower-educated (MBO2) students with digital work instructions compared to higher-educated (MBO4) students using paper-based work instructions. However, no significant differences were found ($U = 132.500$, $p = 0.066$).

3.3 Number of help requests

A significant main effect of both educational level ($F(1) = 10.725$, $p = 0.002$) and type of instruction ($F(1) = 37.273$, $p < 0.001$) on the number of help requests was found. The main effect of educational level indicates that, as hypothesized, in general, higher-educated (MBO4) students made fewer help requests than lower-educated (MBO2) students. The main effect of instruction type indicates that lower-educated (MBO2) and higher-educated (MBO4) students had significantly less help requests, during the assembly task, while receiving digital work instructions as opposed to paper-based work instructions. The interaction effect was not significant ($F(1) = 0.411$, $p = 0.524$), meaning that both lower-educated (MBO2) and higher-educated (MBO4) students benefited equally from digital work instructions.

In Figure 8, also for the number of help requests, a slight benefit is seen for lower-educated (MBO2) students with digital work instructions compared to higher-educated (MBO4) students using paper-based work instructions. Similarly, no significant difference was found ($U = 144.000$, $p = 0.114$).

3.4 Technology acceptance

For the technology acceptance measures, responses across all constructs were quite positive for both paper-based work instructions and digital work instructions. Results of the ANOVA tests show no significant effects of educational level, instruction type or interaction between both factors on any of the constructs as shown in Table 2. Meaning that, in terms of technology acceptance, we didn't find significant differences between lower-educated (MBO2) and higher-educated (MBO4) students, nor between students using digital work instructions and students using paper work instructions.

4. Discussion

4.1 Can we make work for higher educational levels accessible to workers with lower educational levels?

This study set out to examine whether digital work instructions can make tasks typically suited for higher educational levels (MBO4) accessible to workers with lower educational

Table 2. Statistics of the included constructs from the technology acceptance model (TAM)*

	Perceived usefulness	Perceived ease of use	Enjoyment	Behavioral intention	Computer self-efficacy
Factors					
Educational level	F(1) = 0.405, $p = 0.527$	F(1) = 0.706, $p = 0.403$	F(1) = 0.018, $p = 0.893$	F(1) = 0.018, $p = 0.893$	F(1) = 0.244, $p = 0.623$
Type of instruction	F(1) = 0.014, $p = 0.906$	F(1) = 0.011, $p = 0.915$	F(1) = 3.092, $p = 0.083$	F(1) = 0.163 $p = 0.688$	F(1) = 0.002, $p = 0.961$
Educational level * type of instruction (interaction)	F(1) = 0.004, $p = 0.953$	F(1) = 0.508, $p = 0.478$	F(1) = 0.622, $p = 0.433$	F(1) = 1.082, $p = 0.302$	F(1) = 0.369, $p = 0.545$

Source(s): Authors' own work

levels (MBO2). When lower-educated (MBO2) and higher-educated (MBO4) workers receive the same type of instructions, higher-educated (MBO4) workers show better results than lower-educated (MBO2) workers in terms of productivity, quality and independence. At the same time, our results indicate that both lower-educated (MBO2) and higher-educated (MBO4) workers benefit to similar degrees from digital work instructions in terms of productivity, quality and independence. More importantly, lower-educated (MBO2) workers, when supported through digital work instructions, improved their performance to a level comparable to, or exceeding, that of higher-educated (MBO4) workers using paper-based work instructions. This confirms our hypothesis that digital work instructions enable the lower-educated (MBO2) workers to perform tasks graded at a higher educational (MBO4) level.

In terms of productivity, we showed that lower-educated (MBO2) workers using digital work instructions could be considered equal to higher-educated (MBO4) workers using paper-based work instructions. For quality and independence, formal tests of equivalence were not available, but tests on differences were not significant when comparing lower-educated (MBO2) workers using digital work instructions to higher-educated (MBO4) workers using paper-based work instructions. Although it is often speculated that technology can make work more accessible to lower-educated workers, to our knowledge this is the first scientific indication that this can be achieved without negatively impacting product quality or worker independence – an important gain for industries facing tight labor markets. Overall, the findings suggest that digital work instructions increase access to skilled roles by allowing workers with lower educational levels to meet higher-level performance requirements without degrading quality or autonomy.

4.2 Practical implications

In general, working with digital work instructions resulted in favorable outcomes, regardless of the level of education. Working with digital work instructions resulted in an improvement in productivity of 16% for lower-educated (MBO2) workers and 20% for higher-educated (MBO4) workers. Meanwhile, error rates reduced from 7.2 to 3.9 (46%) for lower-educated (MBO2) workers and 4.8 to 1.9 (60%) for higher-educated workers (MBO4) and help requests reduced from 3.3 to 1.0 (69%) for lower-educated (MBO2) workers and 2.0 to 0.35 (83%) for higher-educated (MBO4) workers (median values). The absence of interaction effects indicates that both MBO2 and MBO4 workers could enhance their skills in terms of performance, quality and independence equally through the use of digital work instructions. Besides making work more accessible to lower-educated (MBO2) workers, improving on these indicators could be a goal on its own and is shown to be reachable by higher-educated (MBO4) workers as well as lower-educated (MBO2) workers.

Currently, the accepted quality and performance standard for this type of work is that of the higher-educated (MBO4) workers using paper-based work instructions. Our study indicates that lower-educated (MBO2) workers can be upskilled through digital work instructions and therefore able to reach the required performance levels. However, if higher productivity, quality or independence is beneficial, digital work instructions can also be used to raise the performance on these indicators for higher-educated (MBO4) workers, who often still use paper-based, paper on glass or no work instructions.

Digital work instructions could support work in two extreme labor market situations. A tight labor market encourages more creativity to be able to fill in the vacancies, whereas a loose labor market might impose higher demands on new workers. Digital work instructions could help activate underutilized labor and could also help increase job attractiveness (Eurofound, 2023), whereas if necessary, digital work instructions can be used to reach higher job demands in a loose labor market.

For practitioners, the observed reductions in errors (46–60%) and help requests (69–83%) suggest lower rework and supervisor time, while 16–20% faster execution indicates shorter onboarding to target takt. Because benefits were similar across education levels and no interaction was found, organizations can expect broad, not niche, gains from the deployment of digital work instructions.

4.3 Theoretical implications

We chose a digital work instructions solution that we deemed especially effective for this scenario, which is executed in a static work cell. This makes it suitable to use projection technologies. With these projection technologies, subjects attained a 17–21% higher productivity, 46–60% better product quality and 69–82% better independence compared to paper-based work instruction. In the following literature comparison, we include studies with different scenarios and different digital work instruction solutions that focus on similar outcome measures. We were not able to make comparisons with other literature on the effect of digital work instructions for different education levels since, to our knowledge, this is the first study that studied this effect.

Similar to our results, most studies report benefits of digital work instructions over paper-based work instructions. Two studies found large improvements in productivity (>50%) and product quality (>75%) using *in situ* projected AR (Bosch *et al.*, 2017; Funk *et al.* Oct 26, 2015). This is similar to the projection technology used in the current study, yet with larger improvements found in Funk *et al.* (2015) and Bosch *et al.* (2017). The relatively large effects in these studies might be attributable to the tasks being only a small portion of the full production task, which consisted of picking and placing pieces, an action which can benefit relatively well from projected digital work instructions, while our study included a more varied industrial assembly process.

Studies in which digital work instructions were applied in realistic industrial assembly tasks show results closely matching those found in our study. A study that used animated instructions found that digital work instructions improve productivity (12%) and product quality (52%) (Letmathe and Rößler, 2021). Additionally, Marino *et al.* (2024) found that AR instructions on a tablet improved productivity (20–30%) and product quality (45–47%) compared to paper-based work instructions for both technical students and industrial operators (Marino *et al.*, 2024).

The performance improvements in terms of duration, fewer help requests and fewer assembly errors, observed in our and similar studies using projected step-by-step work instructions, can be interpreted through the lens of the three complexity dimensions (Capponi *et al.*, 2025). Three sources of assembly complexity are distinguished: product-centered (structural), information-centered (informational) and system-centered (procedural) sources of assembly complexity. The projected instructions do not alter the intrinsic structural complexity of the product, but they effectively reduce the operator's experienced structural load by decomposing complex assemblies into manageable, sequentially revealed steps. More significantly, the intervention directly lowers information-centered complexity by minimizing the quantity of information workers must interpret; instead of the need to actively transfer information from a manual to the work bench, operators receive precise, spatially anchored cues that eliminate interpretive ambiguity. Finally, the projected instructions mitigate system-centered (procedural) complexity by enforcing a stable, unambiguous process flow and reducing coordination demands across tasks. By constraining procedural variability and ensuring workers follow the correct sequence, the system prevents common sources of human error and reduces reliance on supervisory assistance. In this way, the improvements we observed align closely with Capponi *et al.*'s theory that assembly outcomes are strongly shaped by structural, informational and procedural complexity drivers. Reducing task complexity through digital work instructions across these dimensions helps to make work more accessible to lower-educated workers.

Furthermore, digital work instructions have the potential to make jobs more accessible to people with disabilities (Looze *et al.*, 2023). Digital work instruction support led to improved quality, reduced stress, greater independence and lower perceived job complexity among people with disabilities (Vanneste *et al.*, 2020). Attention to implementation is essential to fully realize these benefits as a study on people with intellectual disabilities underscores this by showing improvements in productivity, but perceived complexity depended on the level of detail when working with AR instructions (Vanneste *et al.*, 2023). Additionally, a study that analyzed 5 cases in which AR was applied for impaired workers results varied, with benefit in some (productivity (30%) in case 4), but not all cases (case 3 and 5) (Bosch *et al.*, 2020). Additionally, product quality did not change in cases 3 and 5. Although the measured productivity in terms of task-completion time did not always improve, the benefits of AR were there as the impaired participants required less supervision. This suggests higher independence, as found in the present study.

Research on learning within secondary vocational engineering has demonstrated that the transition from theoretical instruction to practical application presents significant challenges (Kollöffel and De Jong, 2013). Students in secondary vocational education are often described as doers, with a preference for visual instructions (Vreman-De Olde, 2006). The visual characteristics of digital work instructions align with these preferences. Nonetheless, it remains debatable whether digital work instructions effectively foster active engagement and meaningful learning as advocated (Kollöffel and De Jong, 2013).

To our knowledge, this is the first empirical evidence that digital work instructions can close an education-linked performance gap (MBO2↔MBO4) on complex assembly tasks, extending prior work that focused mainly on speed/quality gains irrespective of education level (e.g. Bosch *et al.*, 2017; Letmathe and Rößler, 2021).

To complement the objective outcomes (completion time, error rates and help requests), we assessed end-user needs and preferences using constructs from TAM. Overall ratings were positive across conditions, and no differences emerged between digital work instructions and paper-based work instructions. Initial positive findings could be due to novelty effects, emphasizing the need for longitudinal studies that also include subjective measures. This null finding should be interpreted in light of the between-subjects design, which limits participants' ability to make direct comparisons and can reduce sensitivity for subjective measures. A within-subjects design would have increased sensitivity but was not adopted here due to substantial learning effects observed in a preceding pilot, even when different yet comparable tasks were used in each condition. Consistent with the study's primary aim to compare the effect of digital and paper-based instructions on objective outcomes, the TAM results are therefore best viewed as complementary rather than decisive.

The pilot study provides convincing evidence in favor of digital work instructions on subjective criteria: digital work instructions scored significantly higher on experienced usefulness, ease of use, experienced enjoyment and intention to use. Thirteen out of fourteen participants preferred digital over paper-based work instructions, citing fewer errors, higher assuredness and higher efficiency. Worth noting, MBO2 students indicated that they liked being able to perform a task that normally would be too complex for them.

4.5 Limitations

Several limitations need to be acknowledged. First, the projected digital work instructions used in this study incorporated static images and one animated instruction. Evidence on the optimal visualization choice remains mixed: static images appear to be a favorable method for learning by highly developed visualizers (Höffler *et al.*, 2010), whereas other studies report advantages for animations in comparable assembly contexts (Agarwal and Bhandari, 2023; Letmathe and Rößler, 2021). Accordingly, it is not yet clear which visualization methods are best suited for specific groups and contexts, and the present findings should not be over-generalized to different visualization mixes without further study.

Second, one instruction had to be revised after the second measurement day because more than half of the participants in the first two days experienced confusion and made errors on that step. To prevent this mid-study change from biasing the comparisons, all errors related to this action, before and after revision, were omitted from the final results.

Third, outcome assessment for errors and help requests relied on experimenter judgement recorded *in situ*. Although failure modes were predefined and assessors followed a standardized scoring protocol, blinding was not feasible because the projection equipment and other hardware clearly revealed the assigned condition. This lack of blinding may have introduced observer-expectancy effects or subtle differences in how interventions were logged. We attempted to minimize such risks through prior instruction of assessors and use of uniform notation sheets, but residual bias cannot be ruled out.

A fourth limitation concerns ecological validity and generalizability. Participants were technical students rather than experienced industrial workers. They were unfamiliar with the assembly tasks, the structure of both paper-based and projected instructions, and the broader production context. While this allowed us to examine performance differences under controlled conditions, it may have amplified the observed effects (Gugolya *et al.*, 2026) and may also limit conclusions regarding technology acceptance in real-world settings. Additionally, the assembly task was intentionally shortened to comprise 36 rather than 80 steps, with repetitive or low-information activities (e.g. extensive screwing) minimized and battery modules replaced with empty shells for safety reasons. Although this design choice was necessary to ensure feasibility and comparability within the experimental setting, it may limit the extent to which the findings transfer to full-scale industrial assemblies in terms of duration, cognitive load and physical demands. Finally, the effectiveness of projected work instructions is likely to depend strongly on the specific operational context. That is, environmental and organizational factors such as workspace layout, task dynamics, space constraints, lighting conditions, ambient noise, dust and long-term system use may influence system performance and suitability. In particular, projection-based systems may behave differently in dynamic or space-constrained workstations. Current systems also leave room for improvement in terms of context awareness (Fang *et al.*, 2025). Together, these factors suggest that caution is warranted when generalizing the present findings to other production environments.

4.6 Future research

This study highlights the effect of digital work instructions vs paper-based instructions for workers who are faced with a new task. However, it is yet unclear what the long-term effects are. Higher complexity products leave more room for learning, since there are more opportunities for optimization (Verna *et al.*, 2026). Digital work instructions take away some of the complexity, which could lead to less room for optimization and lower performance increases in the long term, possibly evening out the differences between paper and digital instructions over time (Gugolya *et al.*, 2026). Additionally, operators in manual assembly tend to rely on prior knowledge and operate in a know-how manner, therefore ignoring details in instructions when they are more experienced (Johansson *et al.*, 2017), hinting at a need for differentiated work instructions, tailored to the skills and expertise of the worker. A small study ($n = 8$) suggests that a transfer from more detailed instruction initially to more abstract instructions over time support faster and more consistent task execution and might improve learning (Gugolya *et al.*, 2026). Additionally, learning could be affected when following step-by-step instructions. Overly explicit instructions may reduce active processing and hinder knowledge transfer (Berthold and Renkl, 2010). However, the media richness and naturalness theory states that more realistic representations –achieved in digital work instructions through video, animations or augmented/mixed reality – are cognitively easier to process (Kock, 2005, 2009), which frees up more cognitive capacity for learning. Additionally, learning improves when information is presented both verbally and visually, stimulating multiple cognitive regions, according to the dual coding theory and the theory of multimedia, and the multiple resource theory (Clark and Paivio, 1991; Mayer, 1997, 2009; Paivio, 1990; Wickens, 2008). These conflicting theories call for research on the long-term effects of digital work instructions and the impact on learning and internalizing processes.

4.7 Conclusion

Our findings show that digital work instructions enable lower-educated workers to reach established productivity and quality targets. Although participants with higher educational levels (MBO4) outperformed those with lower educational levels (MBO2) when using the same type of instructions, digital work instructions substantially reduced this performance gap. Lower-educated participants using digital instructions performed at a level comparable to higher-educated peers using traditional paper-based instructions: they completed tasks in less time, made fewer errors and requested assistance less often. Given ongoing staffing gaps and rising process variability, these results demonstrate that digital work instructions provide a practical means of elevating lower-educated workers to established performance thresholds. They can effectively support upskilling by improving productivity, accuracy and independence. Beyond enhancing individual performance, digital work instructions also offer potential to address broader labor market challenges by making skilled work more accessible to underutilized groups. As manufacturing environments become increasingly complex, digital work instructions represent a practical and scalable solution for bridging educational gaps and expanding the pool of capable workers. Future research should examine long-term learning effects and assess implementation in real-world production settings.

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