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Evaluation Of An Augmented Reality Qualification System For Manual Assembly And Maintenance

M. König[1], B. Neumeister[1], B. Arndt[1], C. Härdtlein[1], L. Merkel[2], A. Teubert[3], M. Halbauer[4], M. Heller[5], M. Eisenbarth[6], J. Schilp[7]

[1]Fraunhofer Research Institution for Casting, Composite and Processing Technology IGCV, Augsburg, Germany
[2]INOYAD GmbH, Augsburg, Germany
[3]AUDI AG, Ingolstadt, Germany
[4]LUDO FACT GmbH, Jettingen-Scheppach,, Germany
[5]ZFAuerbach, Germany
[6]ZF Group, Alfdorf, Germany
[7]University of Augsburg UNA, Augsburg, Germany

Abstract

Today's manufacturing landscape is faced with a variety of challenges, including globalization, rapidly evolving sales markets, shortened product life cycles, customization, mass production and variant diversity. These trends are expected to continue, if not intensify, in the near future. Companies in this sector identify speed and adaptability of production processes as critical success factors. In order to meet the demands of the market, it is becoming important to deploy personnel strategically and flexibly throughout the entire production process. This increased need for versatility raises the imperative for additional qualification among the workforce. The integration of Augmented Reality (AR) into operational procedures makes it possible to present information in a context-specific and location-based manner by superimposing virtual cues onto the real environment. At the same time, smart glasses can offer a significant and adaptable level of support by enabling the provision of different forms of media while ensuring the availability of both hands. This paper shows results of an ongoing long-term study with the AR-based qualification system AQUA. The software aims to enable the preservation of internal specialist knowledge with minimal effort and to facilitate the creation of training courses that effectively convey learning content to learners without subjecting them to over- or under-challenges. The paper conducts a comparative analysis of employee qualification achieved through AQUA, experienced employee mentoring, and traditional paper-based learning methodologies. It evaluates both the learning quality and duration across these methods, thereby enabling the derivation of insights regarding the potential monetary advantages associated with the utilization of the AR-based qualification approach.

Keywords

Augmented reality; Adaptive manufacturing; Knowledge management; Assembly; Maintenance

1. Introduction

Flexibility is among the key success factor for enterprises in today's production [1]. While automatic and semi-automatic production are particularly suitable for the production of a small number of variants and high quantities, manual assembly offers a flexible method for the fabrication of smaller quantities with a high number of variants [2]. To meet the requirements of the market, companies must deploy employees flexibly

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within assembly operations. This increases the need for additional worker training [3]. Currently, qualification often takes place by means of the "on-the-job" measure "demonstrate – imitate", in which fitters are trained directly on the line by employees who have already been trained. As the training process takes place during series production, this can lead to excessive demands due to time pressure [4]. To meet cycle times, firms often have to interrupt learning processes. There may therefore be gaps in the employee's qualifications [5]. The quality and duration of learning processes can consequently vary greatly between employees [4]. In addition to demonstration and imitation, corporations rely on traditional media such as paper instructions to convey processes. However, these methods pose challenges in translating theory into practice and can be time-consuming and/or error-prone [6]. AR-based systems may offer an improvement by superimposing augmented references onto reality, facilitating situation-specific and location-linked information presentation, thus reducing the burden of knowledge transfer for employees [7]. Head-mounted displays (HMD) are increasingly prevalent across industries including medicine, the military, and sport due to their hands-free operation [8]. Several studies have demonstrated that AR guidance systems expedite assembly processes and contribute to a lower error rate [9] [10] [11] [12]. AR guidance systems provide static assistance and permanently offer a constant level of support. Training/qualification systems do not aim for providing permanent support during production processes. Instead, they train and support individuals until they understand the tasks and can execute them independently. Following the qualification process, employees can then work autonomously, utilizing their acquired skills and abilities. Consequently, individuals can engage in work that is more productive and exercise greater autonomy compared to the perpetual reliance on assistance provided by a guidance system. [13][14]. However, the implementation of adaptive qualification systems that foster learning remains uncommon in industrial settings [15], indicating a disregard for learning requirements and scientific design principles in training course development. AQUA strives to effectively support learners considering their learning progress and thereby distinguishing itself from AR guidance systems. Its design facilitates adaptability to diverse assembly processes, minimizing the effort required for AR training creation. Technical and practical authors, such as foremen, technicians, and supervisors, possess the capability to craft training courses devoid of requisite programming expertise. AQUA targets to ease the extraction and dissemination of experience-based knowledge "from practitioners for practitioners," ensuring broad industry applicability beyond the confines of a research project's demonstration phase.

2. Augmented Reality

AR technologies overlay or complement the real world with virtual objects or information [16]. According to AZUMA [17], AR combines reality with virtuality, is interactive in real time and is visualized in 3D format. FITZGERALD ET AL. [18] consider this definition too restrictive and therefore define a working definition of AR. The authors understand AR as the extension of the immediate environment with digital data and information in a variety of media formats, which include text, audio, video, or haptic overlays. In addition, the information must have contextual relevance to the real environment. KIPPER & RAMPOLLA [19] define AR as an overlaying of digital or computer-generated information in real time with the real world, whereby the overlaid information can extend all five senses. For RABBI & ULLAH [20], AR is a technology that supplements the real environment with computer-generated elements or objects. Furthermore, AR allows for precisely positioned overlaying of real objects with synthetic images in real time, enabling operators to perceive the real environment directly or indirectly. A universal definition for this article results by combining and extracting the essential attributes of literature: "Augmented Reality is the current extension of the real environment with positionally accurate elements. The overlays are interactive and can be visual, auditory or tactile."

3. Learning Theory

When individuals build up knowledge, both privately and professionally, they need to observe some basic principles. ATKINSON & SHIFFRIN [21] significantly influenced research in the field with their model of human memory, which remains relevant today. Accordingly, three domains exist within human memory: sensory (also referred to as ultra-short-term), short-term, and long-term memory. The former serves signal acquisition and allows reproduction for up to a maximum of three seconds. Information in short-term memory also undergo forgetting within a short period, typically up to 30 seconds. Repetition of information extends its retention in short-term memory. However, if individuals do not transfer the information to long-term memory, they inevitably experience forgetting [22]. Ebbinghaus's forgetting curve delineates the rate at which memory retention diminishes over time in the absence of reinforcement. It elucidates that individuals swiftly forget a significant portion of learned information, with the most precipitous decline in recall occurring shortly subsequent to initial learning, followed by a gradual stabilization of retention (refer to Figure 1) [23, 24].

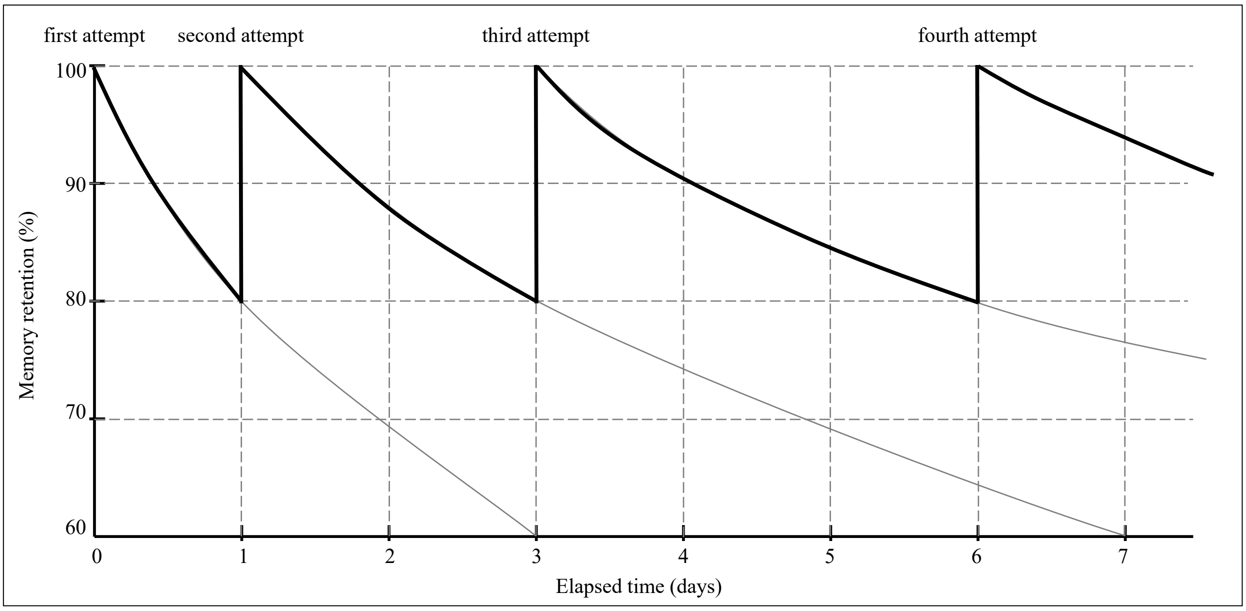

Figure 1: Ebbinghaus's Forgetting Curve [23, 25]

The period starting from the initial acquaintance with a task and ending when the learner attains the ability to perform the task to the desired extent is termed as learning time. During this period, the learner's performance steadily increases. However, neither the individual speed at which the learner acquires the new skill nor the trajectory of the learning curve is predictable [26]. Any information presented to the learner imposes a load on the short-term memory. Exceeding a certain threshold of this load can impair learning [27]. Cognitive overload characterizes the state where learners are overwhelmed by instructional materials, leading to inefficient processing of information and consequently ineffective learning. Both the volume of information and unclear presentation can trigger this overload. To address the issue of cognitive overload, MAYER & MORENO [28] propose five principles, derived from existing research that instructors must consider when creating instructional materials: concentration, temporal contiguity, redundancy, spatial contiguity, and signalling. As previously mentioned, the human brain's capacity to process information is limited. Therefore, the concentration principle advocates for omitting additional information that, while interesting and relevant to the topic, is not essential to the point being learned. When using animations or videos to convey learning content, instructors must maintain temporal contiguity. This principle dictates that congruent explanations should accompany visual content simultaneously rather than before or after to achieve better learning outcomes. The principle of redundancy also plays a significant role. It suggests that presenting text alongside spoken content, such as subtitles, hampers learning success. The learner divides their attention between the two types of media, detracting from the content. A similar principle applies to spatial contiguity, where arranging corresponding elements of information such as graphics and text in close proximity to each other significantly enhances learning. The final principle pertains to signalling. Instructors can facilitate directing attention to essential content and relationships through signals such as dividing content into sections, highlighting key points, or utilizing headings, ultimately positively influencing the learning endeavour [27]. When effectively creating instructional materials, it is imperative to consider these design guidelines. Table 1 shows the 10 system requirements for AQUA prioritised and established with the partner companies:

Table 1: System requirements

I.	Internal preservation of expert knowledge	VI	standardisation of training content
II.	relief for trainers during qualification	VII.	creating incentives for qualification
III.	enabling independent maintenance of skills	VIII.	overcoming language barriers
IV.	flexibilisation of the workforce	IX.	avoiding of over- / underchallenge
V.	applicable for practitioners	X.	fun in learning

4. Methodology

KÖNIG ET AL. [13] established research inquiries concerning AQUA and proposed a methodology for integrating AR-based qualification systems into the organizational framework. Following the development and establishment of an AR-based qualification system within manual assembly and maintenance, the question whether the system improves learning over traditional qualification methods and is monetarily profitable becomes imperative. The evaluation trajectory delineates into three sequential phases, as depicted with dashed lines in Figure 2. The grey area shows the already published system structure [13]. This paper discusses the first two evaluations, while the third evaluation of the AQUA algorithm awaits the conclusion of the ongoing longitudinal study.

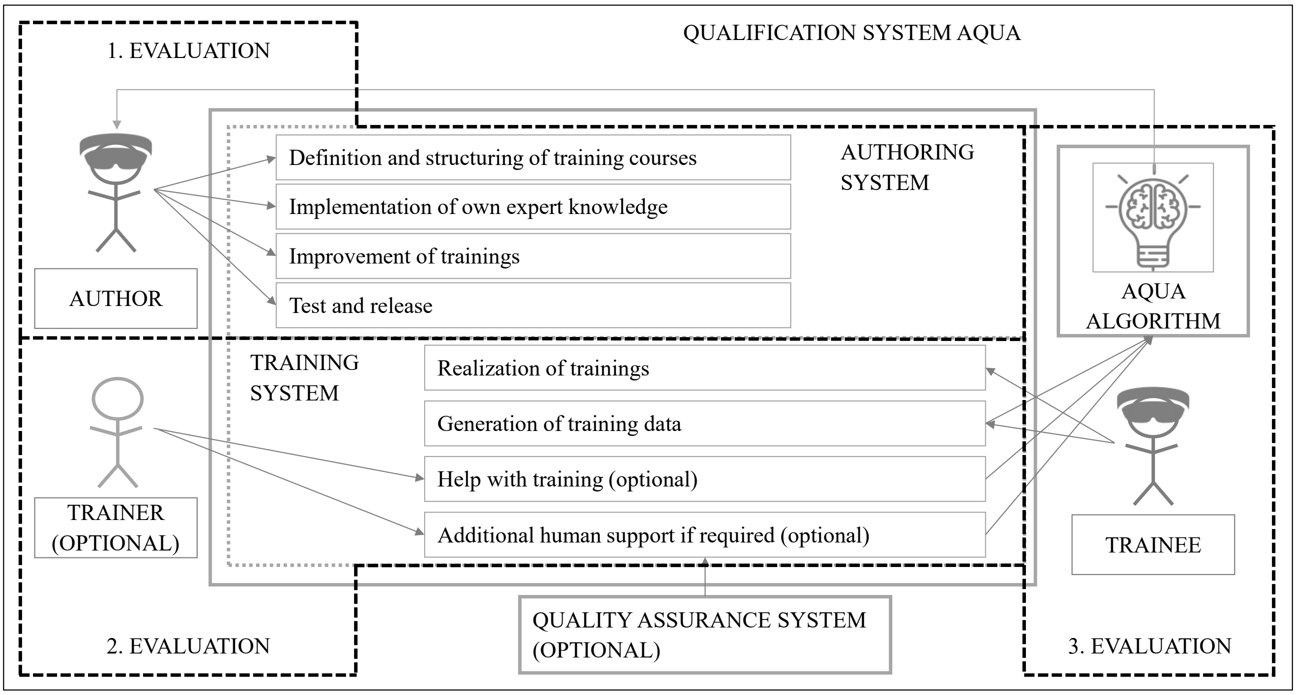

Figure 2: Evaluation of AQUA

As described in [13], authors and trainees act as key stakeholders:

- Authors engage in defining and structuring content, implementing their own expertise, enhancing trainings based on the AQUA algorithm, and conducting testing and release activities.
- Trainees, conversely, execute the exercises and thereby generate data.

The system includes an optional input for external quality assurance systems and human coaches. Given the necessity to ensure broad applicability, we abstain from permanently integrating a specialized testing system for one particular case.

4.1 Evaluation of the AQUA authoring system

The evaluation of the authoring system encompasses both, a qualitative examination of the usability and a quantitative analysis of the effort required for creating training courses utilizing AQUA, juxtaposed with the prevailing standard qualification methodologies employed by the participating companies within the research project. The three participating application companies are currently using the "on the job" and "paper-based learning" methods mentioned in the introduction - which is why these are now being compared with AQUA. The generation of paper-based instructions by the authors occurs within Microsoft Word or PowerPoint (plus smartphone or camera, e.g. for taking pictures), consistent with the historical practices observed within the respective company. Twelve participants, both male and female, with expert knowledge (acting as authors) evenly distributed from the application enterprises, aged between 23 and 58, take part in the experiment. Each author creates two self-selected training sessions with also self-selected scopes (with adherence to the creation rules from KÖNIG ET AL. [23]) for an assembly or maintenance process from their respective companies, once using AQUA and once using a paper-based approach. For example, "author 1 | training 1" is the recommissioning of a robot cell after a fault has occurred due to the accumulation of game boxes. Prior to participation, each author undergoes a standardized AR training session aimed at internalizing the fundamental operations of the smart glasses alongside familiarization with the AQUA system. Table 2 presents the time required by the authors to develop the training courses. A comparison is made between the time needed to develop identical training courses using both AQUA and paper-based methods.

Table 2: Training creation effort

	training creation effort [min]		
	AQUA	paper-based	on the job
author 1 | training 1	48	69	0
author 1 | training 2	61	88	0
author 2 | training 3	57	71	0
author 2 | training 4	41	60	0
…	…	…	…
author 12 | training 24	45	63	0
total	**1442**	**1847**	**0**

Time measurement commences with the initiation of the AQUA application and concludes upon the storage of the completed training. In the paper-based approach, timekeeping begins with the creation of the training document and similarly ends with the final storage. During the experiment, authors using AQUA require approximately 22% less time to create training materials compared to the paper-based method. In the "on the job" approach, authors do not incur creation expenses because they do not need to produce documents but directly impart knowledge face-to-face, thus, the expenses are always associated directly with knowledge transfer. The System Usability Scale (SUS) represents a prevalent tool within the field for evaluating the perceived usability of diverse systems and applications. Offering a standardized approach, it facilitates the quantification of user experience and enables comparative analyses across various systems or iterations. Comprising 10 questions, each evaluated on a Likert scale, the SUS culminates in an aggregate score, thereby reflecting the overall usability of a given system. Two of the 10 questions from the SUS are e.g. “I can very well imagine using the system regularly” and “I find the system unnecessarily complex” [29].

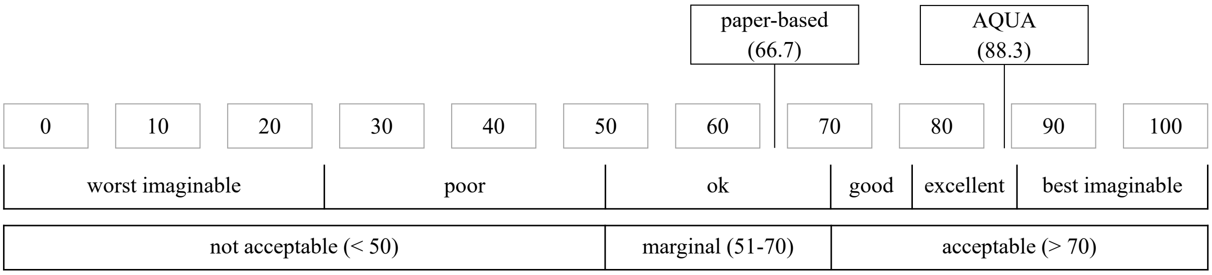

Figure 3: System usability scale

In the context of this experimental investigation, the cohort of 12 authors divides into two equal groups. One group evaluates AQUA using SUS questionnaire, while the other group focuses solely on assessing the efficacy of the paper-based qualification methodology. AQUA attained an average score of 88.3 among the six test subjects, positioning it within the “excellent” category. Conversely, the partially familiar paper-based training creation falls within the marginal range, garnering an average score of 66.7 as shown in Figure 3. The “on the job” approach is not evaluated using SUS, as no technical system is used that could be evaluated.

4.2 Evaluation of the AQUA training system

Currently, eighteen subjects/trainees from the three application companies participate in the longitudinal study. The current participants range from 17 to 54 years of age, encompassing both male and female individuals with varying levels of experience in assembly and usage of data glasses. As described in section 4.1, each enterprise has eight potential trainings available for each of the three systems under test (AQUA, paper-based, on the job). For the evaluation of the training system, five trainings (t1 - t5) out of the eight available are randomly selected from each company and retained for the field trial (see Table 3).

Table 3: Training execution effort

		AQUA [min]					**paper-based [min]**					**on the job [min]**				
		t1	t2	t3	t4	t5	t1	t2	t3	t4	t5	t1	t2	t3	t4	t5
company A	subject 1	65	71	82	105	43										
	subject 2	70	76	90	120	45										
	subject 3						80	101	109	124	50					
	subject 4						77	80	90	98	40					
	subject 5											48	77	80	69	41
	subject 6											48	79	89	70	45
company B	subject 7	161	98	88	156	77										
	subject 8	159	111	94	163	90										
	subject 9						188	123	100	180	91					
	subject 10						193	114	120	182	105					
	subject 11											121	77	61	106	60
	subject 12											132	78	69	110	45
company C	subject 13	140	195	182	163	110										
	subject 14	152	210	176	170	119										
	subject 15						190	214	146	198	166					
	subject 16						181	199	162	181	171					
	subject 17											101	162	121	109	94
	subject 18											161	159	122	116	96
∑		**3611**					**4083**					**2776**				

Each organization tests two subjects with AQUA, two subjects with paper-based learning and two subjects are qualified on the job by the author/trainer. The experimental design of each training adheres to the principles delineated in Ebbinghaus's forgetting curve with training session on day 0, day 1, day 3, and day 6. Once a test subject feels prepared for the respective assembly or maintenance task, they conclude their interaction with the AQUA app, set aside the paper instructions, or inform the trainer in the "on the job" approach that they have acquired proficiency in and comprehension of the task. Table 3 shows the over four learning days aggregated learning time until self-determined completion. The group of subjects feels quickest to be trained and prepared for operational tasks through on-the-job qualification by a trainer. It is to mention, that the same amount of time as the trainee needs to learn must also be spent by a trainer, which is clearly reflected in the later profitability analysis. AQUA ranks in the middle, while the paper-based qualification method constitutes the longest duration of qualification. The rate at which new employees acquire knowledge assumes a secondary significance relative to the quality of learning success. Consequently, a determination is necessitated regarding the parity between AR-based learning employing AQUA and conventional trainer-led (on the job) or paper-based instruction. To test the quality of learning and the transfer to long-term memory, an evaluator assesses the trainee's ability to independently perform the five assembly/maintenance tasks without errors and in the correct order one week, one month, and two months (day 13, 43 and 73) after the completion of the training sessions. The examiner solely observes and under no circumstances provides assistance. Each step of work contributes proportionally to the overall assembly/maintenance process. For instance, in a 12-step assembly training, if a participant performs one step incorrectly and forgets another step, the test result would be 83.3%. The examination is as follows:

- 5 different company-specific training courses are provided in each company
- a total of 6 trainees are trained with AQUA, 6 paper-based and 6 on the job
- five training courses in company A comprise 51 work steps
- five training courses in company B comprise 79 work steps
- five training courses in company C comprise 75 work steps
- a total of 205 work steps are therefore available for testing

Table 4 presents the average respectively 30 conducted tests per company (with six participants undergoing five training sessions each) across the three examination days and per qualification method.

Table 4: Quality of qualification

	work steps carried out correctly and independently [%]		
	day 13	day 43	day 73
Ø AQUA	93	85	84
Ø paper-based	76	63	57
Ø on the job	95	89	83

The results demonstrate comparable levels of qualification efficacy between AQUA and trainer-based learning, whereas the group equipped with paper instructions exhibits significantly weaker learning outcomes. In the test setup, the assumption is that a 1:1 qualification ratio exists between trainer and trainee within the companies. Accordingly, one can retrieve the expenses associated with conducting the qualification measures from Figure 4.

5. Conclusion

The static investment calculation depicted in Figure 4 is predicated upon the subsequent dataset:

- HoloLens 2 costs €3187.71 (the trainer and trainee each use a separate HMD).
- AQUA licence is assumed to cost €2000 per data glasses.
- Electricity, maintenance, and upkeep costs for HMDs are disregarded.
- The hourly rate for a trainer is €43.75; the hourly rate for a trainee is €31.25.
- AQUA amortizes compared to the trainer-based on-the-job method after 197 conducted trainings.
- AQUA amortizes monetarily under the same assumption after 1264 conducted trainings compared to the paper-based learning method (regardless of the inferior learning quality with paper).

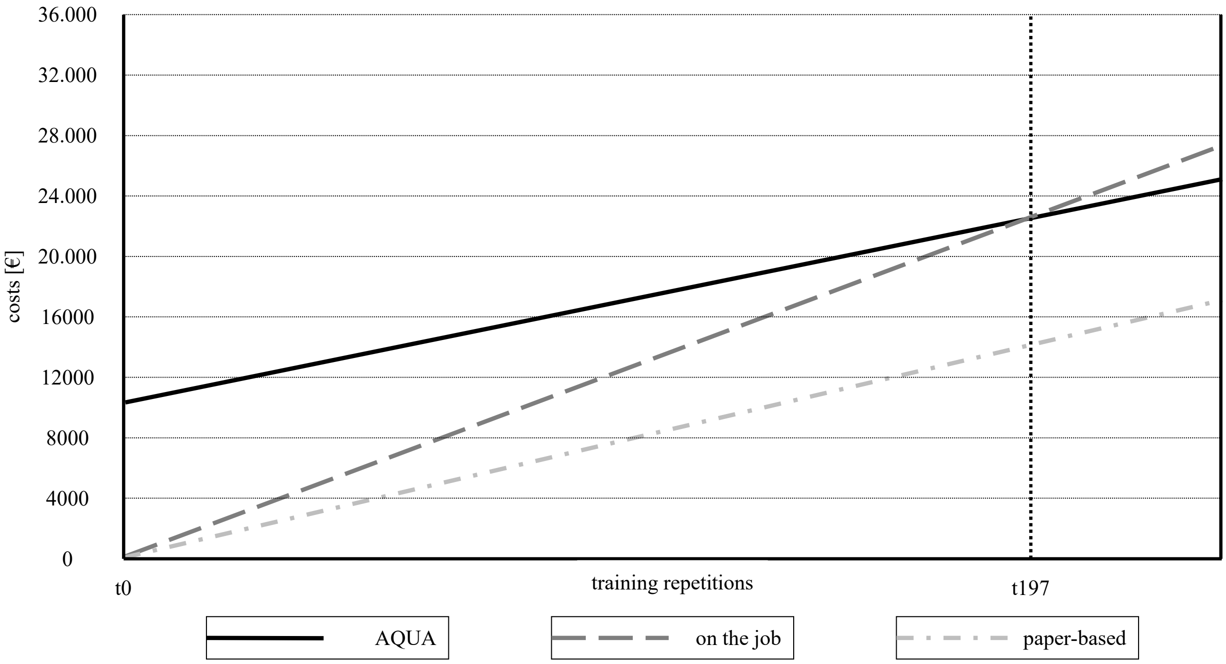

Figure 4: Static cost accounting

Consequently, AQUA is to be regarded as a more economical alternative compared to traditional training formats such as paper-based or human-led sessions. The evaluation of the authoring system demonstrates that AQUA enables faster training material creation with higher author acceptance/usability compared to the paper-based method. On-the-job qualification does not involve the design of instructional materials, thus preventing a direct comparison with the AQUA authoring system/methods. During the field trial, test subjects learn fastest with a human trainer (23% faster than with AQUA). Paper-based qualification significantly lags behind in this aspect. Comparing the essential quality of the different qualification methods, it can be concluded that similar amounts of assembly/maintenance knowledge were retained in the long-term memory of the subjects through AQUA and human trainers. After two months, the newly acquired skills and abilities could still be performed at 83% (on the job) and 84% (AQUA), respectively, while in the group learning with paper instructions, only 57% of the tasks could be performed independently. AQUA presents promising opportunities for enhancing learning processes. A subsequent publication on the evaluation of AQUA training data analysis will demonstrate whether the continuous evaluation of training data yields internal operational benefits. Through the integration of further media forms such as artificial intelligence (AI) or remote assistance, AQUA can further leverage its potential, rendering the system even more versatile and capable.

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Biography

Maximilian König (*1990) studied industrial engineering at the University of Augsburg. Since 2018, he has been working as a research associate in the field of cognitive assistance systems at Fraunhofer IGCV. He leads various research projects and is doing a doctorate at the University of Augsburg.

Benno Neumeister (*1986) studied industrial engineering at the University of Augsburg. Since 2023, he has been working as a research associate in the field of cognitive assistance systems at Fraunhofer IGCV.

Benedikt Arndt (*1999) is currently studying business informatics at the University of Augsburg. He works at Fraunhofer IGCV as an auxiliary scientist.

Christian Härdtlein (*1991) is head of department for flexible production automation. He leads various research projects and is doing a doctorate at the Technical University of Munich.

Dr.-Ing. Lukas Merkel (*1990) received his doctorate from the Technical University of Munich in the field of cognitive assistance systems. He worked for Fraunhofer IGCV as research associate from 2016 to 2020. Since 2020, he is managing partner of INOYAD GmbH in Augsburg.

Adam Teubert (*1970) is a technical officer in manufacturing at Audi Ingolstadt, specializing in assembly. He manages the production of various product lines.

Marcel Halbauer (*1984) is head of automation and robotics at Ludo Fact GmbH since 2020. He is tasked with orchestrating the automation of all processes spanning the value chain across multiple locations. Prior to this role, he served as a team leader overseeing the application of human-robot collaboration.

Maik Heller (*1975) is head of plant launch management & lead plant at ZF‘s plant in Auerbach in der Oberpfalz since 2024. He is responsible for the sample production of the power units and supervises the small volume line. He is also responsible for launch management and coordinating the task of the lead plant. Before that, he was 30 years in leading positions at Boge, NXP, Phillips and VW.

Dr.-Ing. Michael Eisenbarth (*1970), senior vice president operations, is responsible for global production and supply chain management withing the passive safety division at ZF Group since 2020. The division is developing and producing airbags, inflators, seatbelts and steering wheels in more than 30 plants globally. Before that, he held various leading management positions at Delphi, Continental and Vitesco Technologies for over 20 years in the automotive business. In addition to other honorary positions, he is also member of the advisory board of the German Assembly Congress.

Prof. Dr.-Ing. Johannes Schilp (*1976) has held the chair of production informatics at the University of Augsburg since 2015. He is also head of a main department at Fraunhofer IGCV, head of the Innovation Advisory Board of the Swabian Chamber of Industry and Commerce, and, among other honorary activities, an advisory board member of the German Assembly Congress.