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Augmented reality for understanding electronic components in vocational education

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ABSTRACT

Understanding the structure and operation of electronic components is challenging when instruction relies on two-dimensional media because their internal processes are not directly visible. This study developed and evaluated a marker-based Augmented Reality (AR) learning medium for Electronic Components in a vocational Industrial Electronics Engineering programme. Using a Research and Development approach based on the ADDIE model, the AR medium was developed with Unity and Vuforia to provide interactive 3D visualizations of electronic components, including rotation, scaling, and animations of their operation. The medium was validated by three electronics specialists and three media design specialists using Aiken's V, while its practicality was assessed by one teacher and 15 tenth-grade students. Conceptual understanding was measured using a 20-item pretest-posttest administered to the same 15 students. Material and media validity scores were 0.888 and 0.955, respectively, indicating very high validity. Practicality ratings were also very high, reaching 93% from the teacher and 92% from the students. Mean conceptual understanding scores increased from 41 on the pretest to 80.33 on the posttest, with an N-Gain of 0.67, categorized as moderate. Although the one-group design does not establish causality, the findings indicate that AR-based visualization can support students' understanding of abstract electronic concepts and provide a practical instructional model for vocational education.

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Introduction

As digitalization of the production industry increases at a higher speed, and this process is generally described in the context of Industry 4.0 and Society 5.0, the demands on technical and vocational education and training (TVET) systems worldwide have undergone changes in respect of competences. Vocational institutions nowadays have to ensure their students possess skills not only on conceptual literacy but also on advanced automation and precision technologies that will be a constant feature in their workplace. This need has been one of the major factors pushing secondary vocational schools to change their instructional model to one that is digitally enabled and learner-centered (Fortuna et al., 2024). In fact, in the general transformation that took place, the vocational programs related to electronics remain highly significant because electronics Technicians are required to have the ability to interpret theoretical principles, such as the internal composition, function and operation of a component, into skills like being able to analyze circuits, assemble them, as well as identify and eliminate faults. Because component-level reasoning underlies circuit analysis, assembly, and fault-finding alike, difficulty visualizing how a component works internally is a plausible bottleneck for these broader Industry 4.0

competencies, although other factors such as general digital literacy and systems thinking may also contribute and are not ruled out by the present study.

In terms of conceptual difficulties, electronic components, as teaching materials, are considered difficult. Their structures are not physically visible, their functions are based on abstract physical phenomena like charge flow and field effects, and their circuit behavior is difficult to deduce simply by looking at them. If the students are only taught these facts through the medium of diagrams, two-dimensional drawings, or the lecture-style method, then students are expected to create mental models for hidden processes through indirectly-presented information, and such a practice will always leave the students with a partial or totally wrong picture of the reality (Asham et al., 2023), since students will hardly understand everything that is shown or described to them. In fact, such problems were observed quite generally and not only by the institutions of higher learning; studies of AR technology utilization in electrical and electronics engineering education reveal that there has been a continuous, fundamental, disconnection between how abstract electrical and magnetic phenomena are and how much instructional equipment are able to represent and illustrate them (Asham et al., 2023; Iriqat et al., 2025).

This particular problem is something that was already proved empirically, before designing the product. An initial check of Grade X Industrial Electronics Engineering students at the research site had a mean achievement score of 69 only, against the required minimum passing score level of 75. The students showed only 52.4% overall competency (mastery rate). The achievement was actually lowest at those very indicators which call for analysis of working principles and application of components in circuits from 42.9%-52.4%) rather than rote identification of symbols (61.9%). The pattern that appeared was aligned with other evidence on vocational electronics learning: students are able to memorize formulas and figures and still remain incapable of understanding and reasoning behind the concepts and principles of devices especially when the teacher heavily uses non-interactive or low-interactivity media for instruction (Rozi & Anwar, 2024). This baseline achievement test was a school-administered mastery test tied to the KKM standard rather than an independently validated research instrument, so it is reported here only as descriptive evidence motivating the intervention, not as a psychometrically established measure.

At the same time, the same student population also had almost 100% access to the necessary technological equipment that a mobile AR environment needs: Every surveyed student had an Android smartphone of their own, 90.5% of them were in the habit of bringing the device to school every day, and 90.5% had already started using their phones for learning-related activities. However, only 52.4% among them had been using any interactive learning apps beforehand. This combination -a theoretically understood conceptual difficulty together with a high level of technology readiness that is still under-used for visualization through structured images provides the practical basis for this research and agrees with general findings that the rate of vocational learners owning smartphones in Indonesia has now largely surpassed the amount of teaching and learning activities that are carried out using smartphones (Fortuna et al., 2024).

AR has been the most theoretically sound and supported answer to this particular instructional challenge. When one uses augmented reality a learner gets a real-time camera-like view of the surroundings, but with a twist. Over a real-world scene, AR will put some three-dimensional, virtual material that one can interact with. By giving a chance for learners to touch, rotate, and inspect virtual objects, AR opens a door to the study of those that one cannot physically see or reach while at the same time the learner is still physically located in the classroom rather than being entirely virtually isolated (AlGerafi et al., 2023). From the point of view of how the mind works, such a capability also dovetails nicely with the Cognitive Theory of Multimedia Learning (CTML) that basically says that to make an idea stick you should be showing something and also talking or writing about it. The theory suggests that to build mental models you should present both verbal and pictorial channels of information together, instead of showing the verbal or the pictorial, and that the best scenario would be if the cognitive load brought by the interface remains low compared to the effort required by the cognitive processes to understand the learning content (Mayer, 2021). Research into how the load of the mind is distributed in the context of AR teaching has really sharpened the above view of the situation: Conceptual learning through AR, it turns out, is not a given but the product of the ways in which the spatial relationships, the highlighting of what's important, and the extent to which one can interact with the information (the interactivity) are woven together in the AR application, a poorly designed AR even having the capacity to impose a cognitive load that is more or less the same as the cognitive load of other methods but less than the cognitive gain of it all (Altmeyer et al., 2024; Gonnermann-Müller et al., 2025; Nurjanah & Retnowati, 2024; Suzuki et al., 2024).

Empirical evidence about educational impact or effectiveness of AR has increased quite significantly in recent years although the scale of evidence and the consistency of effect are dependent on the context. Citation network analysis of AR and VR research shows, at a broader level, the field is being defined increasingly by learning outcomes and interactive environments themes that reflect real-life challenges rather than pilot studies driven by the novelty factor (Zhao et al., 2023). Utami et al., 2022 have used bibliometric methods to map the development of the field and this study further supports the claim made previously that the number of research work published in the area of engineering education combined with AR continues to increase over the last decade. This body of literature includes a meta-analysis study involving 134 studies that were quasi-experimental or experimental on AR between 2012-and-2021. That meta-analysis concluded that the largest benefits of AR intervention were observed for low-level learning outcomes such as skill mastery and performance, in comparison to the more distant measures such as attitude changes (Chang et al., 2022). Subject-specific research reviews have revealed very different effects of technology on student learning in engineering education and STEM education. They report generally, medium-to-large effects of AR on learning outcomes such as conceptual understanding and skill acquisition. At the same time, the researchers caution that the duration for which the treatment is conducted, the subject being taught, and how one designs the instruction are among the factors that are likely to determine the size of the effect (Hidayat & Wardat, 2024). On the other hand, both literature and content reviews in technical and vocational education have consistently shown a link between AR and improvement in student engagement, motivation and understanding of concepts in simulated or practice-type TVET settings. However, the research papers also state that despite being so, implementation in schools at that level has been restricted not only due to the high cost and lack of infrastructure but the instructors' readiness in utilizing the technology to its full potential, too (Fortuna et al., 2024; Peng et al., 2025; Ramadhan et al., 2024). What a research paper published a little after in 2024 by Yuniarti and colleagues found interesting was that the educational impact of AR does not end there. They demonstrated with their experimental work that it goes hand-in-hand with AR implementation in pre-service teacher education. When AR supported activities aimed at higher order thinking skills were introduced to pre-service vocational teachers, they gained self-regulated learning skills, digital skills and most importantly, critical thinking abilities which are vital indicators of learning (Yuniarti et al., 2024).

Specifically in the areas of electronics and electrical engineering education, the use of AR devices for visualizing various circuit elements and how they work internally have been part of several recent studies.An application that is AR-based for showing the working of circuit of operational amplifiers was created with the help of combining ADDIE-based instructional designs with agile software development methods. Using a smartphone camera, learners can direct the camera to a physical breadboard marker and thus, they will get insights into the relationship between input-output, underlying formulas, etc. Just lately, a vocational school in Indonesia created an AR-based interactive media for a foundational electronics course that aimed at raising the low level of student enthusiasm in the face of a conventional instruction. The authors shared the same rationale that has been documented in this study. In another line, the literature reviews on AR for engineering psychomotor and technical skills training that were done systematically reported positive effects in the cases of skills that require visualization or physical actions (Chan et al., 2022).

Although the amount of evidence is growing, there are still some gaps that are relevant to the present work. Firstly, at the instructional side, it is well known by the literature that the understanding of internal structure and work principle of electronic components is one of the main problems of students. This is even though the technological resources needed for the task are available digitally. (Rozi & Anwar, 2024) Second, from a technological perspective, the use of conventional 2D and print-based methods of component presentation restricts the opportunity for the learner to be active in inspecting the component from multiple angles, which is precisely the ability that AR can provide. However, for the senior-secondary vocational level electronic-component content, there is no solid empirical documentation yet (Asham et al., 2023). Third, at a practical level, there is not a lot of evidence on the use of AR technologies specifically in the electronics programmes for TVET-track. Unlike general STEM or higher-education engineering contexts. TVET-AR-related studies have usually focused on those which were different from electronics specialization or which were outside the secondary-level vocational education (Fortuna et al., 2024; Ramadhan et al., 2024). fourth, in terms of empirical research, only a small number of electronic-education AR papers provide a complete set of evidence that includes, expert-validated content and media quality, independently rated teacher and student practicality, and pretest-posttest conceptual gain as proof of learning within a single coherentely designed product (Iriqat et al., 2025; Maulidannisa & Ansori 2024). Fifth, from a design-related point of view: only a few papers combine the display of 3D components (which includes the ability to rotate/zoom the object), animated working principle sequences, and vocational instructional context into an effective empirical instructional package, but these are generally treated as separate design features (Simon, 2023).

Based on the synthesis, building a learning medium through the development and application of marker-based augmented learning tools for the Electronic Components subject in the Industrial, circuit Engineering subject in Grade X through the ADDIE model. The researcher, instead of presenting the paper as a record of one institution's product developmental diary, highlights an main point the development of the AR visualization environment is a well-founded instructional response to the gap in the vocational electronics education. What makes this paper different is not the use of AR as a technology, rather it is through combining three dimensional component visualization marker based interactivity working principle animation and vocational instructional context that has been subjected to a complete validity practicality effectiveness evidence trail particular to TVET electronics.

In line with that, the paper investigates three topics in this paper how much the media of the developed AR learning medium for electronic components is deemed valid, respectively by the subject matter expert and the media expert, etc. As much as the teacher and the students who actually used the medium found it to be suitable; what proof or support for a link between exposure to the medium and changes in conceptual understanding of Electronic Components among different students could there be?

Theoretical Background

This thesis is guided by three strands of theoretical perspectives that interlock and support one another. First, Mayer (2021) has articulated a Cognitive Theory of Multimedia Learning (CMM) in which it is stated that learners can develop understanding more deeply and efficiently if the presentation is a joint delivery of words and pictures that align with each other through a dual-channel mechanism and working memory limitations in both channels are simultaneously respected. From a theoretical stand- point, AR-enabled teaching represents a feasible way to practically implement this principle whereby 3D visualizations of electric devices could become the perfect complement to written explanation, audio recording, and animation of operating principles which are literally pinned to the physical piece being examined. Despite the aforementioned, studies on cogni-tive-load theories that look into AR have revealed that the advantage is, however, conditional. On the one hand, AR is able to decrease the load via an effective spatial contiguity design in the interface. On the contrary, it might end up doing more harm by making the interface even more complex or overloaded, thus turning users off. The point here is that it is not the AR technology per se that makes the learning more or easier. Rather, the choices regarding the instruction are at play to determine if AR is either facilitating learning or getting in its path (Altmeyer et al., 2024; Gonnermann-Müller et al., 2025; Suzuki et al., 2024).

Second, research studies in the area of visualization and conceptual understanding in engineering and science education show that abstract, non-observable phenomena are a constant source of student misunderstanding. Furthermore, the combination of visual representation and interactive simulation is found to decrease the risk of student misunderstandings because it allows the learners to see explicitly the connection between an abstract concept and its physical representation. For electronic components, the literature mentioned here implies that the real value of AR is not just visual appeal or decoration but a carefully scaffolded form of instruction that links the physical, internal, symbolic, and working features. This four-fold characterization is the same that was used in the present study for expert validation to assess material validity.

Third, constructivism and experiential learning theories as applied to vocational education suggest that TVET students learn best through active, inquisitive interaction with materials that are close to real technical practice, and that such interaction is far better than just receiving information (passively). This viewpoint aligns with progressive education's idea that learning takes place when we do something and reflect on our experience as well (Dewey, 1938). This learning perspective supports the choice of an interface consisting of touch, gesture and scanning functionalities (finger tapping, rotating, zooming, and marker scanning) as an engaging and learner-centric model as an opposition to the classical static (video/slideshow) way. The reasoning here is that vocational students get a better concept by interacting with the materials themselves instead of watching.

To begin with, at the level of implementing TVET-specific technology, Fortuna et al. (2024), Peng et al. (2025), and Ramadhan et al. (2024) identified similar findings: a) AR consistently leads to an increase in learner engagement and conceptual results in TVET, but b) adoption rates are fluctuating, and quality of execution differs significantly from one study to another. This indicates that rather than relying on general AR-in-education conclusions, the field still needs well-designed, context-sensitive, and scientifically grounded development studies.

Fig. 1 shows how the three theories come together in the conceptual framework of the study: the pedagogical, technological and contextual deficits detected in Chapter 1 are what lead to an AR-based solution which draws upon CTML and constructivist/experiential learning theories, and is measured with the help of results related to validity, practicality, and conceptual-understanding from Section 4.

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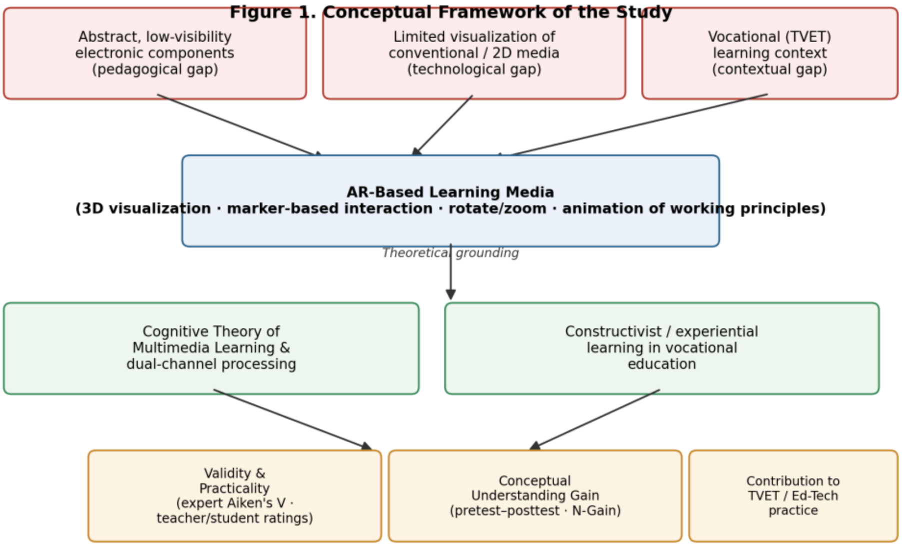

Figure 1. Conceptual framework of the study.

Method

Research Design

This research employed a Research and Development (RND) type design based on the ADDIE model which stands for Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009) as a framework for creating and assessing a Augmented Reality-based learning material on Electronics Components topic. The choice for the ADDIE model came from its systematic and cyclicality which is a structure that not only can carry out a needs analysis but also iterative refinement of a product and a true empirical validation of its validity practicality, and effectiveness are combined into a single procedure suitable for the creation of instructional media for vocational education.

Participants

The research took place at a public vocational high school (SMK) specializing in the Electrical Installation department (Electronik Industri). The research and the effectiveness test (pretest, posttest) were conducted with a small group of Grade X students 15 students in total the primary research subjects. Later, these same 15 students, one subject teacher, did the practicality assessment to make things simple. The team also did a validation of the product by six experts, the first three subject matter (materi) experts were specialists in electrical /vocational education with related qualifications, last the three media experts, had credentials in teaching technology and instructional medium development. They all separately evaluated and commented on the product. An initial needs assessment had been carried out using a larger group of electrical installation (Electronik Industri) Grade X students (21), who were the sources for the initial achievement and technology-readiness findings of those mentioned in Section 4.1. Both the 21-student needs-assessment group and the 15-student effectiveness-trial group were drawn from the same Grade X Electronic Industri cohort using purposive (intact-class) sampling rather than random selection; the smaller effectiveness-trial group reflects the single class section that was available and consented to take part in the full validation-practicality-effectiveness cycle at the time of implementation. No a priori power analysis was conducted, and the resulting sample size is acknowledged in Section 7 as a constraint on statistical generalizability.

Development Procedure

Analysis

The first stage of our work was analysis which entailed examining initial conditions, concepts, and learner characteristics together.Initial-conditions analysis came first and it pointed out that teaching mainly used textbooks and two- dimensional media. In addition, the mean test score was 69, but the minimum required to be able to move to a mastery level was 75 (52.4% total mastery). Also, the lowest mastery areas were working principle analysis and applied/circuit reasoning.The concept analysis took the Grade X Electronic Components curriculum and categorized passive and active components as well as their associated symbols, functions, and basic working principles.We also analyzed the learners' characteristics. It turned out that almost all (100%) of them owned smartphones, with almost all (90.5%) stating they had used their phones in schoolwork. These findings suggest that they are technologically ready to implement a mobile AR learning program even though very few (52.4%) had previously been exposed to interactive learning apps.)

Design
The design phase was responsible for turning the ideas into an instruction plan that would specify details of a circuit diagram visualization system such as different types of electronic elements like a resistor, a capacitor, a inductor, a diode, a transistor. It would also define what marker set was going to be used for object recognition. Besides that, it would lay out the interaction procedure of (marker scan→3D component display→information display→component-guided action→animation explaining the working principals). The evaluation plan consisted of expert validation rubrics, two types of questionnaires teacher and student practicality, together with a 20-item multiple-choice conceptual-understanding test that was administered before and after the activity.

Development
Unity was main environment that allowed developers to create AR application. A marker recognition and image tracking capability was supported by the plugin Vuforia. This development practice corresponds to one of the usual technical methods of implementing mobile, marker-based augmentation reality in educational environments. For the interaction with specific components through C# scripting such as tap, zoom, rotate, slider controls etc., we also made animations of working principles of things, the example being an animated representation of electron flow, in the form of a pipeline. The application was developed in such a way as to be compatible with Android handsets, which were the kind of devices students would likely have been bringing along to this experiment.

Implementation
A single 15-person research subject group, with students being provided the validated product, were subjected to one instructional session. Students brought their individual Android devices to the class that day to carry out the task with the physical markers and the resulting 3D components which appeared visually using Augmented Reality (AR). All were conducted under teacher facilitation and in a standard lesson sequence where first they were given application orientation, then the students explored each component through teacher guidance and finally they connected AR visualization of the different components to the underlying working principles with teacher facilitation. Right before the implementation was started the students were given a pretest, and when the session was over they were given a posttest. The teachers together with students filled the practicality questionnaires after their instruction had finished.

Evaluation
During this phase, the evaluation of validation, practicality and effectiveness was carried out through the synthesis of the mentioned results in order to check the product on the basis of pre-determined validity, practicality and effectiveness, apart that it also was used as a means to uncover the changes which are required for the final report.

Learning Media Characteristics
The developed software is a marker recognition-based AR application compatible with Android devices. Major aspects are the following: 1- realistic form and size 3D view of components, 2- a marker that, when printed or digital, is the only one to be recognized linking it to its 3D model, 3- the touch interaction where one clicks, pinch, and drag controls can be directly manipulated, 4- each element's textual and/or audible description of its function and features, 5- animation sequences of inner workings like flow of current or electrons were specially added to tackle the gap of principle master which the previous analysis indicated.

Instruments
Four different types of instruments were used. First, materials were validated by experts who evaluated the content in terms of curriculum alignment, content's completeness and correctness, accuracy of the explanation of the working-principle, and support for conceptual understanding, with each of the three independent experts rating them. Meanwhile, media-verification tools by the experts were through a 35-item questionnaire that measured, among others, visual design, functionality of application, ease of use, interactivity, and instructional suitability. Practicality assessments involved two parallel 20-item instruments, one for the teacher and the other for the students, both delivered after utilizing the product, and addressing, basically, how pleasant, easily understood, time consuming and beneficial the product perceived by the students and how useful and easy for the teacher. The understanding-assessment test, in the form of 20 multiple-choice questions and identical with regard of the content of symbols, functions, and working mechanisms of passive and active electronic parts, served as both pretest and posttest to allow score comparing directly.

Data Analysis
Expert validation data were analyzed with Aiken's V coeffi cient, which is essentially a measure of content validation agreement quantified for raters who have agreed to a limited rating scale; a validity criterion of $V \geq 0.5$ was adopted, in line with the usual interpretation guidelines for this coeffi cient (Aiken, 1985). Practicality data, on the other hand, were measured not as a percentage in the context of maximal attainable score but rather

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as a percentage of maximal practicality, which was subsequently interpreted in correspondence with the pre-set practicality classifying scheme (with those who have attained percentages in the higher tier being interpreted as "highly practical". The pretest and posttest scores are reported as descriptive measures in terms of their minimum, maximum, and mean scores. In addition to the Gain Score, which is the difference between the mean posttest and mean pretest scores, we also computed the N-Gain, the normalized form of the gain, to describe how much the students improved from their pretest until the posttest. The formula used to normalize the gain and the category bands (low, moderate, high), however, corresponded to the ones set up for the pretest-posttest learninggain analysis (Hake, 1998). Anti -fabrication principle is an important issue in our research work. Following this principle, all of them, the inferential statistics that are based on individual raw data beyond the source data that was reported (e.g. standard deviation, p-value, effect size from raw score distributions which are not reported) are not included; the absence of such data is made clear if such an analysis is not compatible with the available data (e.g.).

Results and Discussion

Needs Analysis

I strongly believe that through a good baseline assessment, a teacher will know the learning level of his/her students, thus a teacher can make necessary preparations. Here is the evaluation summary of our students' Electronic Components achievement for Grade X Industrial Electronics Engineering (21 students) which is presented in Table 1. The average score reached the value of 69, a figure less than the requirement standard of minimum mastery (KKM), i.e., 75. There was a total of 52.4% of students who mastered the subject material. As it can be observed in the results, there was a higher accomplishment in symbolic recognition (72; 61.9% mastery) compared to analyzing the operating principle (68; 52.4% mastery) and circuit-application reasoning (66; 42.9% mastery). Thus, the main obstacle was not component identification, rather it was the ability to think and understand how the components work and are implemented.

Table 1. Baseline Achievement and Technology-Readiness Indicators (N = 21 Students)

Indicator	Mean score / n	KKM	Mastery (%)
Identifying component symbols	72	75	61.9
Explaining component function	70	75	57.1
Analyzing working principles	68	75	52.4
Applying components in circuits	66	75	42.9
Overall mean	69	75	52.4
Owns a personal Android smartphone	21 (100%)	-	-
Brings smartphone to school	19 (90.5%)	-	-
Uses smartphone for learning	19 (90.5%)	-	-
Prior experience with interactive learning apps	11 (52.4%)	-	-

Note. KKM = Kriteria Ketuntasan Minimal (minimum mastery criterion). Source: baseline evaluation and student technology-use questionnaire administered prior to product development.

Meanwhile, the technology readiness survey of this same group showed that all 21 students (100%) had their own Android smartphones, 19 (90.5%) were bringing them to school most of the time, and 19 (90.5%) were already using them for educational purposes. It is, however, worth highlighting how a minority of just 11 students (52.4%) had prior interaction with learning applications that featured an interactive component. Taken together, these results imply that if anything was hindering learning, it was neither technological access nor its availability that were the limiting factor, but the fact that no educational visualization software was available that could make use of this technological access. It is precisely this deficit that the AR technology was originally created to tackle.

Development of the Augmented Reality Media

The AR application was developed according to the ADDIE stages outlined in Section 3.3, resulting in the creation of a marker-based Android application that teaches the passive and active electronic components from the standard Grade X curriculum (Figure 1). Versions of the application were revised at the development phase as per the experts' input. These changes finally resulted in the enhancement and fine-tuning of three characteristics before the product was validated and implemented: (i) a major performance issue with manipulating 3D objects has been fixed by enhancing the rotational control of the three-dimensional object; (ii) for each component, a bit of additional textual or audio information has been included; (iii) the calculation of the resistor color code was added so that the students have the opportunity to play with it and change the color band codes that they see into the value that represent the resistance directly in the app. This also can be very useful because it allows students to learn how to do the color-band code to resistance value conversion in the easiest possible way. Figure 2 presents the storyboard of the application, illustrating the full screen flow from the splash screen through the main menu, material menu, quiz menu, marker menu, and AR scanner, to the component display, student-identity entry, quiz questions, and final score screens.

Table 2. Development Features of the Augmented Reality Learning Media

Feature	Description
Platform	Android (smartphone/tablet), matching students' existing devices
Development environment	Unity, with Vuforia for marker-based image recognition and object tracking
Interaction scripting	C# scripting for tap, pinch-to-zoom, drag-to-rotate, and slider controls
Visualization	Three-dimensional models of passive and active components (e.g., resistor, capacitor, inductor, diode, transistor)
Working-principle animation	Animated sequences depicting internal processes (e.g., electron/current flow)
Supplementary content	Per-component textual information and audio narration
Applied feature	Resistor color-code-to-value calculator (added during revision)
Interaction sequence	Marker scan → 3D object display → component information → guided interaction → working-principle animation

Note. Feature specification synthesized from the Development and Evaluation stages of the ADDIE procedure described in Section 3.3.

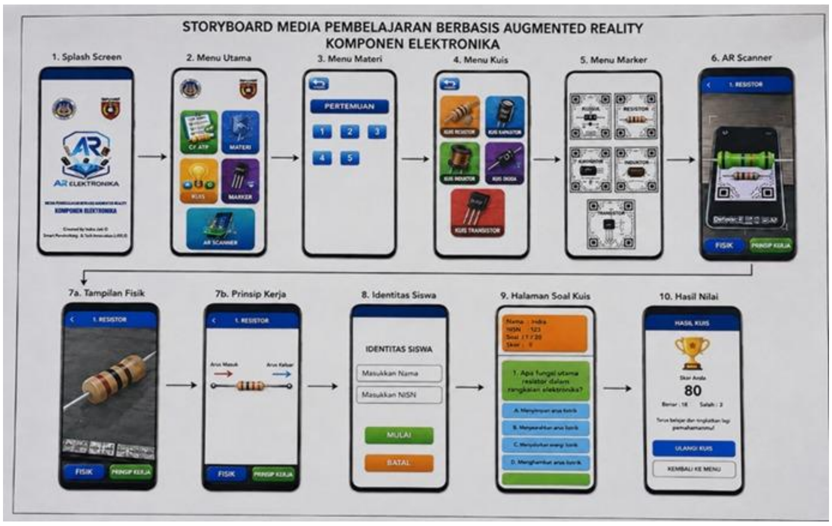

Figure 2. Storyboard of the Augmented Reality learning media application (screen flow from splash screen to quiz results).

Full-resolution storyboard available at:
https://drive.google.com/file/d/1AqWjkJKyNIPrGHXa_LVjiYvcccG_44Qm/view?usp=sharing

Expert Validation

Material validity as judged by three subject-matter experts in four aspects, yielded a mean Aiken's V value of 0.888 overall, classifying as a valid instrument (Table 3). Aiken's V validity for the instructional material as assessed by three media experts in five aspects, came in an overall mean of 0.955, likewise classifying as a valid instrument (Table 3). Aiken's V values of individual items ranged between 0.750 and 1.000, and all items exceeded 0.5 in terms of validity thresholds these results showed that both the learning material and the medium's technical/ design qualities were found worthy for use before classroom execution and empirically grounded the conceptual framework which underpins the study's overall design logic.

Table 3. Expert Validation Results (Aiken's V)

Instrument	Aspect	Aiken's V	Category
Material validation	Alignment of material with learning objectives	0.938	Valid

Instrument	Aspect	Aiken's V	Category
Material validation	Accuracy and completeness of material	0.896	Valid
Material validation	Accuracy of component working-principle presentation	0.854	Valid
Material validation	Support for conceptual understanding	0.896	Valid
Material validation	Overall mean	0.888	Valid
Media validation	Visual design	0.940	Valid
Media validation	Application functionality	1.000	Valid
Media validation	Ease of use	0.964	Valid
Media validation	Interactivity	0.929	Valid
Media validation	Suitability for classroom use	0.940	Valid
Media validation	Overall mean	0.955	Valid

Note. Aiken's V ≥ 0.5 was applied as the validity criterion (Aiken, 1985). Material validation was rated by three subject-matter experts; media validation was rated by three media/educational-technology experts.

Practicality

The teacher-rated practicality, with 4 different teacher rating factors (ease of use, time efficiency, attractiveness, and benefit) averaged the highest total of 93.00%, and was categorized as "highly practical" (Table 4). Teacher-rated practicality across 15 students produced individual scores of 88% to 97%, an averaged student-rated score of 92.00%, and this too was categorized as "highly practical" (Table 4); furthermore, all 15 students rated the medium as "highly practical, " meaning that there was a consensus among the students rather than a mixed opinion response pattern. The teacher-rated figures in Table 4 are based on a single respondent (n = 1) because only one subject teacher taught the participating class; these percentages are reported as that individual teacher's judgment and are not intended to be generalized to teachers as a population, unlike the student-rated figures, which are averaged across 15 independent respondents.

Table 4. Practicality Results (Teacher and Student Ratings)

Rater	Aspect	Result	Category
Teacher (n = 1)	Ease of use	92.5%	Highly practical
Teacher (n = 1)	Time efficiency	95.0%	Highly practical
Teacher (n = 1)	Attractiveness	90.0%	Highly practical
Teacher (n = 1)	Benefit	95.0%	Highly practical
Teacher (n = 1)	Overall mean	93.0%	Highly practical
Students (n = 15)	Range across respondents	88%–97%	Highly practical (all respondents)
Students (n = 15)	Overall mean	92.0%	Highly practical

Note. Teacher practicality was assessed with a 20-item questionnaire; student practicality was assessed with a parallel 20-item questionnaire administered to all 15 effectiveness-trial participants. Category bands follow the pre-established practicality classification described in Section 3.6.

Learning Outcomes

Pretest scores (n = 15) ranged from 20 to 50, average was 41.00; posttest scores ranged from 75 to 90, average was 80.33 (Table 5; Figure 3). The resulting gain was 39.33 points, normalized gain (N-Gain) was 0.67, categorized as moderate (Table 5). The average posttest score (80.33) not only matched but went a little beyond the minimum mastery criterion of school (KKM=75) obtained in baseline needs assessment while the average pretest score (41.00) was very much below it such a pattern although not evidence definitely suggests a change in understanding resulting from the use of AR medium. Figure 4 presents all five components of the evaluation (validity of content, validity of medium, teacher's feasibility, learner's feasibility, and normalized gain) compared by a common scale.

Table 5. Pretest, Posttest, Gain Score, and N-Gain (n = 15)

Statistic	Pretest	Posttest
Minimum score	20	75
Maximum score	50	90
Mean score	41.00	80.33
Gain Score (posttest mean − pretest mean)		39.33

N-Gain	0.67 (moderate)

Note. N-Gain category bands (low, moderate, high) follow Hake (1998). The 20-item multiple-choice conceptual-understanding instrument was identical for pretest and posttest.

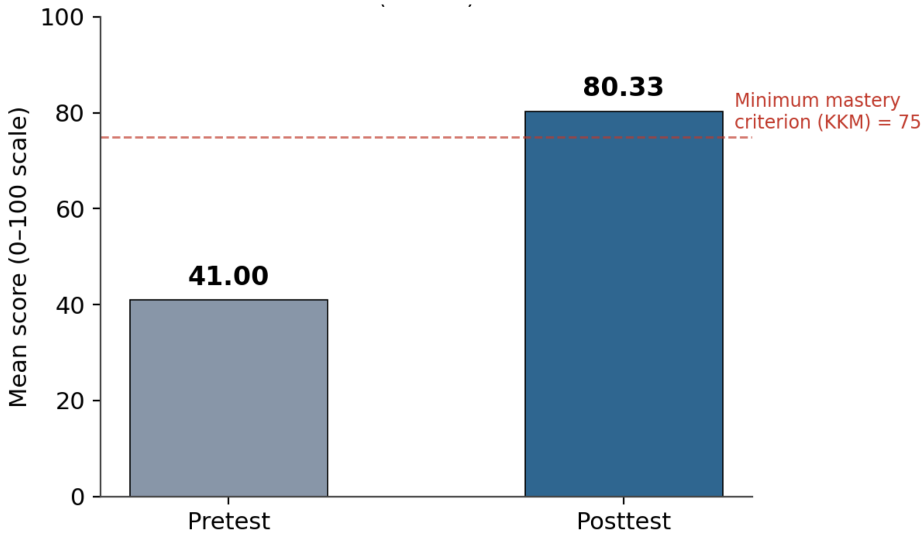

Figure 3. Comparison of pretest and posttest conceptual-understanding scores.

Product Revision

A few months down the lane after development work, a comprehensive product redesign was done incorporating expert review along with classroom experimentation findings, primarily targeting only those three aspects found and discussed in prior development revision work (three-dimensional turning characteristics, per-component display along with audio content, and the resistor color-code calculation feature) to prepare and complete the product design so that it can be considered as a classroom tool.

Figure 4 gives an overview of the complete evaluation cycle of the study, physical validity, media validity, teacher practicality, student practicality, and N-Gain, plotted on a single scale for the purpose of direct comparison. Besides that, it also shows the empirical grounds for the following discussion in a very compact manner.

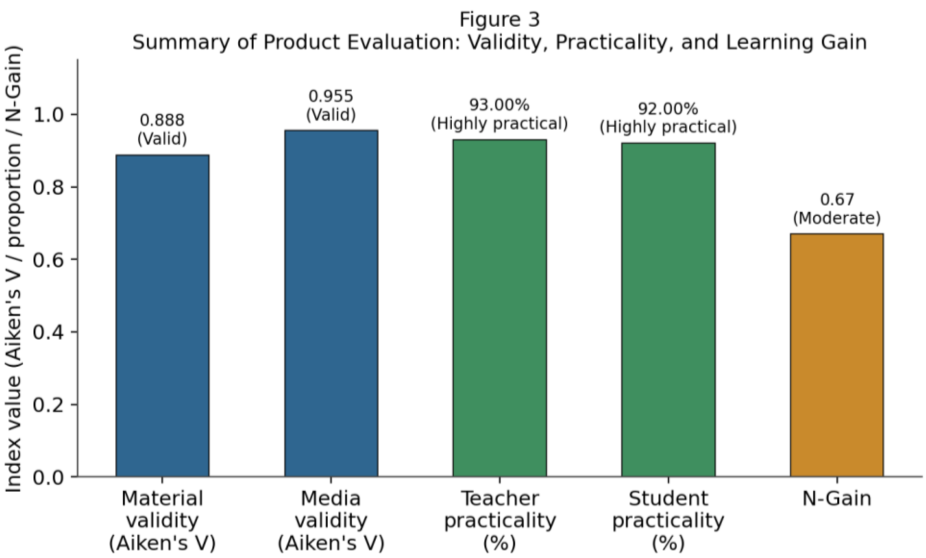

Figure 4. Summary of product evaluation: validity, practicality, and learning gain.

Validity as evidence of instructional-design coherence

The content and media validity results (Aiken's V = 0.888 and 0.955, respectively) revealed that the experts who worked independently from the researchers found the instructional content as well as the implementation of technical aspects of this mixed reality tool to be quite suitable for the classroom. This result seems to align with the recent studies on electronic development for AR that reported very good expert-validation scores on AR products developed by instructional system designers through methods such as ADDIE (Iriqat et al., 2025; Maulidannisa & Ansori, 2024). If we were to take this validity result as an end, we would miss an important interpretation of it. The better interpretation of the findings points to the fact that those decisions about instruction which are reflected in section 3 for instance, the deliberate linking of the four aspects of content validity with the identified mastery-gap of working principles were instrumental in making the product whole or at least close to whole without taking for granted that the product could be considered valid as a matter of course simply because of the novelty effect of AR. This point is crucial to understand because if you only look at the experts' validation scores in and of themselves, they reflect the level of the design more than the degree or extent to which it impacts learning; In this study, the importance of validating the design via expert opinion is that it helps to establish that these results on the usefulness and effectiveness of teaching with such materials must have originated from a set of learning resources which have been vetted by independent experts rather than being just a random untried out product.

Practicality and the role of learner-controlled interaction

In the case of the practicality ratings given by teachers and students they were rated as highly practical with no student rating below 88%. This consistency across 15 independent student raters implies that there was a genuine shared perception of usability rather than a small or a particularly favorable subsample artifact. Such a trend is more or less similar to practicality outcomes in other vocational and ADDIE-based learning media reported in different AR-based scenarios where both teacher and student practicality ratings clustered in the "highly practical" range (Maulidannisa & Ansori, 2024). From the constructivist perspective outlined in Section 2, it seems that the direct-manipulation interaction model (tap, zoom, rotate) enabled students to be actively involved with the instructional content rather than being passive recipients of information, which vocational learners may particularly appreciate due to the practice-oriented nature of TVET instruction generally (Fortuna et al., 2024). On the other hand, practicality is no substitute for effectiveness of a learning product; in fact, these two lines of evidence can be thought of as different in nature, which is why we, in this study, decided to present them separately and to interpret them in their respective contexts as well.

Interpreting the conceptual-understanding gain

The N-Gain of 0.67 is at a moderate level. It is an indication that conceptual understanding scores moved in a significant way from pretest to posttest yet they changed neither insignificantly nor completely that there was a ceiling effect. Since one-group pretest, posttest design was used in this study, the best way to describe the outcome is that the AR medium was linked with the conceptual understanding change and not to say the material led to such change since no alternative condition was given and other influences like the maturation, testing, or instructional context effect could not be ruled in. In this context, the finding is quite close to the effect sizes that come out larger in AR meta-analyses which also involved a mixture of different educational settings and longer intervention times (Chang et al., 2022; Hidayat & Wardat, 2024), a distinction that can be reasonably ascribed to this study's brief, single-session intervention and its small sample size, both of those features have been openly recognized as limitations in Section 7. The finding is typical and has been observed not only with AR but also with other technologies. The meta-analytica! findings of technology-enhanced STEM instruction, a larger category, as well, mention only limited, rather than universal, improvements in achievement by means of single technology interventions, which implies that a fairly large N- gain is likely and acceptable outcome if a brief single-session technological intervention is implemented and not that the material did not perform up to the expectations. The effect of such a change cannot however be underestimated, considering the context: The average of the posttest scores surpassed the minimum required level of mastery at the school, while the average of the pretest scores fell below the level. This indicates that the gain was not only detectable statistically but also had instructional consequences.

One plausible theoretical account for the aforementioned trend in Section 2 is cognitive. We suggest that the 3D visualization and working principle animation in the AR medium helped alleviate student working principle reasoning difficulties (as opposed to symbol recognition) by visualizing the otherwise "internal" causal process and making it available to be experimented upon. This kind of explanation fits well with cognitive-load theory which emphasizes that the instructional worth of AR primarily lies in whether its use enables learners to focus effort on the hard-to-see and visualize aspects of the content by reducing distractions and facilitating mental restructurings, whereas it's not the AR per se that is so motivating.

Comparison with related studies

While a similar ADDIE-based design process to operational-amplifier AR lab work developed at the university level for engineering education, the current research applies the same general design strategy marker-based recognition combined with highly informative visual 3D interactivity to a secondary-level vocational lectronics setting where full cycle of validation, practicality and effectiveness is done, the comparator study focused mainly on technical application development with limited evidences for learning outcomes. Around secondary-level science instruction with AR, validity and practicality of the present study fall largely the same high percentage as those of the previous studies, implying that the instructional design procedure, not the domain of subject matter, is the more consistent factor affecting the validity and practicality of AR-based educational media (Maulidannisa & Ansori, 2024; Yusro et al., 2023). When compared to the Indonesian vocational-school study tackling a similar electronic instruction issue via AR-based interactive methods, the present work has introduced an N-Gain measurement of conceptual understanding effectiveness as a quantitative complement to that study's almost entirely design-and-implementation orientation. Taken together, both contribute to the growing consensus and context-specific evidence that AR is an effective tool for visualization of complex concepts as has been well-documented in the case of Indonesian vocational electronics education (Rozi & Anwar, 2024). With respect to the wider landscape of TVET-AR studies pointing out consistent but diverse results of student engagement and conceptual understanding across several vocational areas, the current study's moderate N-Gain fits within the range of results usually seen for brief, single-lesson TVET AR interventions rather than exceeding it (Fortuna et al., 2024; Peng et al., 2025). Beyond the two AR-development studies discussed above, the present N-Gain also sits within the moderate-to-large range reported by broader AR meta-analyses outside TVET electronics specifically (Howard & Davis, 2023; Wang et al., 2022), and it is consistent with the pattern, noted in recent AR-motivational-design and bibliometric reviews of vocational education, that engagement and conceptual gains from AR tend to be positive but uneven across implementations depending on instructional design quality rather than the technology itself (Muskhir et al., 2024; Prasetya et al., 2024). This broader comparison set remains modest relative to the size of the AR-in-education literature as a whole, and a systematic review dedicated specifically to TVET-electronics AR studies is identified as a direction for future synthesis rather than something this single empirical study can substitute for. Table 6 compares the present study's main indicators next to three recent, AR/ADDIE-based development studies using a similar research methodology.

Table 6. Comparison With Recent Related Studies

Study	Context	Development model	Validity	Practicality	Effectiveness indicator
Present study (2026)	Vocational electronics (Grade X, TVET)	ADDIE	Material 0.888; Media 0.955 (Aiken's V)	Teacher 93.0%; Student 92.0%	N-Gain 0.67 (moderate)
Iriqat et al. (2025)	Engineering (electronic circuits laboratory)	ADDIE + agile	Reported valid/functional (qualitative + expert review)	Not reported as a percentage	Not reported as N-Gain
Maulidannisa & Ansori (2024)	Lower-secondary science (PjBL)	ADDIE-based R&D	Media 84.72%; Material 83.30%	Student response 88.46%	Reported effective; N-Gain not directly comparable
Yusro et al. (2023)	Lower-secondary science (electronic worksheet)	4D model R&D	Rated "very good" by experts	Not reported as a percentage	Reported effective for outcomes and interest

Note. Metrics are drawn from each study's reported validity/practicality/effectiveness indicators as described in the cited sources; direct numerical comparison should be treated with caution given differing instruments, scales, and educational levels.

From the comparison in Table 6, two trends can be identified. In the first trend, the validation and practical figures of this present study are generally in line with similar studies based on the ADDIE model and, in the case of media validation, are slightly higher. As this indicates, the instruction design process does reasonably well as a generalizing concept in different areas of teaching. The second trend highlights that only a small number of comparison studies disclose an effectiveness measure as defined in this study using normalized gain, so it is hard to make exact comparisons of effect size. It can also be reasonably interpreted as confirming the practical problem addressed by this research, validity-practicality-efficacy triad studies within the realm of AR-in-electronics-education are still relatively rare.

Practical Implications.

For teachers

Beside for teachers, the augmented reality platform fits most in the role of an added visualization element embedded by a teacher within a guided learning environment rather than serving as a totally independent substitute for teacher explanation. Practicality data indicate teachers are likely to get a highly user-friendly platform Effectiveness data, on the other hand, point to a conceptual benefitIt is therefore most likely to be very beneficial when it is deliberately discussed by combining the AR visualization to reasoning behind the mechanisms of work the very area of misunderstanding the medium was created for.

For schools
Given the close to universal existing smartphone ownership documented in the needs analysis, institutions may be able not needing to procure any new hardware if they choose the same type of medium. On the other hand, providing the application, a good Wi-Fi connection or local file-sharing system besides printed or displayed AR marker will still be a major requirement.

For TVET institutions more broadly
The evaluation process, expert verification, and the independent assessment of teachers and students regarding its usability are among the factors that make this chain of evidence quite convincing. The results of pretest –

For curriculum developers
The recognition that it was a working-principle reason but not a symbol recognition reason that explained the gap in understanding is an example of how a very detailed, indicator-level needs analysis can guide decisions on where visualization technologies should be used within a curriculum, instead of just applying AR uniformly to every piece of instruction content that is presented to learners.

For educational-technology developers
Alongside marker-based identification, direct-manipulation operation, and working-principle animation, rather than merely showing static 3D model, the resulting feature set is the core of the design reasoning in several research works including the present one, which yielded the best validity and practicability scores. The fact that such feature combination has given consistently good results over the studies suggests the feature combination as a starting point or reference for designing similar AR educational products (Simon, 2023).

Limitations
This study points out a number of limitations that readers must be aware of if they want to understand and criticize the present findings. First, the number of students in the effect study was small (15 students only) which is a significant limitation of statistical and practical generalizability of concepts of understanding of the results. Thirdly, effectiveness was mainly assessed through the use of a multiple-choice test of knowledge of concepts; it is quite possible that the results of a conceptualunderstanding-based test are not the same as if, for example, the students are motivated by, or engaged in the learning process, or the students are good at troubleshooting. The last one is that the research team did not check if the gains in concepts of understanding would be retained or get progressively higher after the immediate posttest, so there is no evidence about whether a student's conceptual understanding continues to be strong or weak over time. Finally the researchers did not measure or assess practical skill transfer (hands-on) through conceptual-understanding, eg, a physical circuit assembly or a fault diagnosis, which remains an independent skill in the field of vocational electronics. Also the team did not do a long-term follow-up learning effects over time of a series of lessons since the implementation is only once. Future study should look up these shortcomings with bigger multi-location samples randomized or quasiexperimental controls comparison conditions delayed posttests to check retention and directly measured transfer of actual skills from a conceptual understanding.

Conclusion

Because a one-group pretest-posttest design without a control group was employed, the results reported below should be interpreted as evidence that the AR medium was associated with, rather than proven to cause, an improvement in students' conceptual understanding. This study developed and evaluated a marker-based Augmented Reality learning medium for the Electronic Components topic in Grade X Industrial Electronics Engineering vocational education, using the ADDIE model to structure a complete validity–practicality–effectiveness evaluation chain. The medium was judged valid by independent subject-matter and media experts (Aiken's V = 0.888 and 0.955, respectively) and was rated highly practical by both the teacher (93.00%) and students (92.00%). Conceptual-understanding scores increased from a mean of 41.00 at pretest to 80.33 at posttest, corresponding to a moderate normalized gain (N-Gain = 0.67). The study's principal contribution is empirical and context-specific: it provides a complete, transparently reported evidentiary chain for an AR visualization environment purposefully designed around a documented instructional gap in vocational electronics education, and it offers TVET practitioners and educational-technology developers a replicable instructional-design template centered on marker-based recognition, learner-controlled interaction, and working-principle animation. The findings are appropriately understood as evidence that a valid, highly practical AR medium is a promising and potentially effective - rather than definitively proven - response to a well-documented conceptual-visualization gap in vocational electronics instruction, pending confirmation through larger, controlled, and longer-duration studies. Future controlled trials confirming this association should plan for a substantially larger sample per arm than the present n = 15 to have adequate power to detect the observed effect size with confidence.

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