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The Role of Cognitive Learner Prerequisites for Cognitive Load and Learning Outcomes in AR-Supported Lab Work

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Abstract: Augmented Reality (AR) can enhance student-centered lab work by bridging the spatial and temporal split between virtual information and observed real-world phenomena. While the Cognitive Theory of Multimedia Learning and the Cognitive Load Theory suggest that AR can reduce extraneous cognitive load (ECL) and foster learning, the empirical results remain inconsistent. This re-analysis of three related studies with different target groups and AR devices explores whether learners' spatial abilities and verbal working memory capacity moderate the effect of AR support in lab work settings on ECL and conceptual knowledge gains. Although these moderators could not be confirmed consistently, the results indicate that tablet-based AR holds the potential to support learners with low spatial abilities. Moreover, low verbal working memory learners were demonstrated to be particularly vulnerable to the spatial contiguity failure that can be caused by smartglasses AR. Moderation effects were only observed for ECL but not for conceptual knowledge gains. The findings highlight that the benefit of AR support can depend on learners' cognitive prerequisites and additional contextual factors, such as the AR device used and the age of the target group. The design and implementation of AR-supported lab work environments should account for these factors to optimize the learning outcomes.

Keywords: augmented reality; science education; lab work; cognitive load; individual differences; spatial ability; verbal working memory

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1. Introduction

Considered a key feature of scientific work, hands-on experiments are an essential part of science education. Augmented Reality (AR) can support this instructional approach by integrating virtual learning information into real-world experimental setups. The resulting real-time spatial integration of real phenomena and virtual information is assumed to reduce split attention, potentially reducing learning-irrelevant cognitive load and contributing to improved learning outcomes in science experiments (e.g., [1]). In the course of an interdisciplinary research project on the use of AR to enhance physics lab work, we empirically investigated this theoretical assumption in three studies. While the three studies were based on similar AR-supported learning environments, they varied in the AR technology employed and the sample characteristics. Contrary to theoretical assumptions about the effects of AR, we found mixed, negligible, or even contradictory results on cognitive load across the three studies. This aligns with a recent research synthesis also reporting contradictory effects of AR on cognitive load levels [2]. Moreover, in contrast to the numerous meta-analyses that have already demonstrated the potential of AR for enhancing learning (e.g., [3,4]), our studies showed ambiguous effects of AR on learning outcomes. Our findings led to the conclusion that the potential of AR to improve learning processes may depend on a variety of factors, including technical and pedagogical implementation but also learner prerequisites. Prior studies have indicated that spatial abilities and verbal working memory capacity are critical in processing information from various sources (e.g., [5]). Although these cognitive learner prerequisites seem to be promising factors that could contribute to the explanation of the ambiguous effects of AR in educational settings, their impact on learning within AR environments remains largely unexplored. In this current research, we re-analyzed our three studies on AR-supported physics lab work to shed light on how individual learner differences in spatial and verbal processing influence the effect of AR on cognitive load and learning outcomes across different samples and AR technologies.

1.1. Augmented Reality to Support Learning in Lab Work Settings

AR refers to settings where real-world environments are supplemented with virtual information [6,7]. It thus ranges on a continuum between purely real and purely virtual environments and is assigned to the upper term Mixed Reality [8]. AR can be implemented using different devices such as head-mounted displays (HMDs; e.g., smartglasses) or monitor-based interfaces (e.g., tablet PCs). There is broad meta-analytic evidence showing that AR is a beneficial tool in education that can support learning processes (e.g., [3,9]). Moreover, AR seems to be particularly common and helpful in science-related disciplines [4,10].

Experimentation in lab work settings is considered a fundamental aspect of science education that aims to provide students with opportunities to acquire essential conceptual knowledge and procedural skills [11,12]. Lab work has recently emerged as a particularly promising field for educational AR applications [13]. For instance, Akçayır and Akçayır [14] demonstrated that AR not only enhanced students' laboratory skills in a university physics course but also fostered positive attitudes towards physics labs. Further, AR can facilitate the creation of hybrid multiple external representations (MERs) by spatially and temporally integrating virtual learning representations—such as single measurement values or scientific models—into a real-world experimental setup. This integration is particularly expedient as conventional lab work settings often suffer from a spatial and temporal disconnect within multiple sources of essential information: Additional information typically has to be presented on worksheets or separate displays that are not spatially linked to the experimental observations or components, do not adapt in real time, and are often presented before or after the actual lab work.

There are numerous examples of applications that have made use of AR-based hybrid MERs in lab work settings, considering different target groups and devices. For example, Lauer et al. [15] described an AR application, applicable for both AR tablets and smartglasses, that provides real-time adaptive visualizations of electrical circuit schematics. These virtual visualizations are spatially attached to real circuit components (e.g., resistors and cables) and aim to support elementary school children in mentally linking the components and corresponding schematics. Donhauser et al. [16] presented an AR-supported experimental learning environment on the topic of Lorentz force for secondary education. They used smartglasses to enrich physical observations with virtual visualizations of magnetic fields and vector triads. The studies to be re-analyzed in this current work investigated physics lab work scenarios on electricity education. In all studies, AR was used to spatially integrate time-adaptive measurement values into the physical experimentation environment by means of AR smartglasses [17] or tablets [1,18].

1.1.1. Theoretical Background

Instructional psychology provides several complementary theoretical approaches that can be applied to explain the positive effects of the hybrid MERs created by AR for lab work. The *Cognitive Theory of Multimedia Learning* (CTML; [19]) is grounded in the assumption of the dual coding of information [20] in separate verbal and pictorial working memory channels with limited processing capacity. According to the CTML, learners process information more effectively when it is presented through a combination of both verbal and pictorial representations (multimedia effect). After selecting and organizing the relevant elements of single verbal and pictorial representations, learners have to perform a complex integration process to mentally link the representations with each other and with prior knowledge. According to the temporal and spatial contiguity principles derived from the CTML [21], presenting representations close to each other in time and space enhances the mental integration processes by relieving the working memory. Thus, these principles underscore the importance of aligning the relevant learning information to promote learning processes.

The *Framework of Coherence Formation* [22,23] draws a distinction between two consecutive mental integration mechanisms needed for the successful processing of MERs: Selection and organization processes to map relevant elements within single representations are subsumed under the term *local coherence formation*. Subsequent *global coherence formation* describes mental mapping processes across mental models of different representations and results in an integrated mental representation. In line with the CTLM, the framework states that the spatial and temporal integration of information facilitates global coherence formation and fosters learning.

Both theories explain the positive effect of information presented in a spatially and temporally integrated manner (e.g., hybrid MERs created through AR) by reducing the cognitive costs of limited working memory resources. Increasing the distance between representations is assumed to increase the working memory load by necessitating learners to retain larger units of information between gazes, which can manifest in fewer gaze shifts and longer information processing intervals [24]. The composition and interplay of the cognitive costs attributed to learning processes is described by *Cognitive Load Theory* (CLT; [25,26]). CLT distinguishes three categories of cognitive load pertinent to learning: Intrinsic cognitive load (ICL) is determined by the level of the task-inherent complexity of information. Germane cognitive load (GCL) is assumed to result from the active processing of learning information. Extraneous cognitive load (ECL) depicts the task-irrelevant processing caused by the design of instructional material and should be minimized to optimize the cognitive capacity available for effective learning. The most common method to measure the three types of cognitive load in a differentiated way is by using retrospective subjective rating scales. In recent years, a variety of cognitive load scales have been developed that have individual focal points and have been shown to cover different aspects of cognitive load (e.g., [27–29]). From a CLT perspective, AR is assumed to reduce ECL in lab work settings by avoiding split attention [30] between experimental phenomena and the corresponding information necessary to understand the underlying mechanisms and concepts. Consequently, AR-enhanced learning setups are expected to result in higher learning gains compared to conventional split-source experimental settings (e.g., [1]). The systematic review of Buchner et al. [2], however, presents mixed findings regarding the influence of AR on cognitive load, indicating that the effect of AR may depend on a variety of moderating factors, the relevance of which may, in turn, depend on the specific learning domain.

One factor that might impact cognitive load in AR-supported learning environments is the AR device used. Against the background of theoretical and practical considerations, Thees et al. [17] discuss the advantages and disadvantages of the different AR devices used in lab work settings. Compared to smartglasses, most teachers and learners are more familiar with screen-based augmentation by means of easily accessible and affordable handheld tablet PCs or smartphone cameras. However, the redundant visualization of the experimental environment by these devices (i.e., students see objects twice: on the tablet display and as a physical object behind the display) could induce additional ECL (see also [31]). In contrast, HMD devices such as smartglasses provide learners with a more immersive experience through a stronger sense of spatial and temporal blending between virtual and real representations. Moreover, they enable hands-free interaction during experimentation. A recent meta-analysis on AR in science learning [4] found no significant influence of the particular AR device used on academic achievement. However, the limited number of included studies using HMD devices considerably limits the conclusions.

1.1.2. Re-Analyzed Studies

The three studies re-analyzed in this paper originate from the interdisciplinary collaborative research project GeAR ("Gelingensbedingungen und Grundsatzfragen von Augmented Reality in experimentellen Lehr-Lernszenarien entlang der schulischen Bildungsbiographie" which translates to "Success factors and fundamental questions of using Augmented Reality in experimental teaching and learning scenarios across the educational pathway"). This project addressed various success factors of AR in student-centered laboratory work through several empirical studies.

Based on the theoretical assumptions described above, we conducted three related studies to investigate how AR can enhance physics lab work scenarios on electricity education. All studies compared an AR-supported condition with a separate display condition. The AR condition created spatial and temporal contiguity by spatially integrating time-adaptive measurement values into the physical experimentation environment by means of AR smartglasses [17] or tablets [1,18]. The separate display setup induced split attention between the real experimental setup and the measured values presented as a matrix on an external tablet display. All studies hypothesized an advantage for the integrated AR presentation format of the measurement values, which was expected to manifest in lower ECL levels and higher conceptual knowledge gains. However, the effects of the integrated AR presentation were mixed across the studies.

The first study under investigation [1] examined a sample of university students and found no differences between the conditions in either of two different ECL scales employed. Nevertheless, in line with the hypotheses, the AR-supported condition showed moderately higher learning gains.

The second study [17] used smartglasses-based AR in an experimental setting for university students, which was very similar to the first study [1]. Contrary to expectations, the separate tablet display condition caused less ECL and was superior in terms of the conceptual knowledge test items closely related to the instruction. However, differences in ECL were only present in one of two employed ECL scales. The results highlight the potential drawbacks of smartglasses and provide evidence for the so-called spatial contiguity failure [32]. The integration of measured values into the experimental environment broke up coherent structures between the measurement values. Because of technical limitations regarding the field of view of smartglasses, subjects in the AR condition were not able to observe all measured values at once. This spatial fragmentation was assumed to impede referential connections and coherence formation within measurement values, which were necessary for conceptual understanding.

The third study [18] adapted the electricity lab work setting for a target group of elementary school children. The AR visualizations were realized by tablets placed in fixed positions. The results showed that AR had no significant impact either on ECL or the conceptual knowledge test performance.

To sum up, the effects of AR across our three studies that investigated different AR devices and samples were mixed and often did not confirm the theoretical assumptions. Following evidence on learning with MERs (e.g., [33]), so far unconsidered individual differences in learners' prerequisites may have acted as moderators that concealed expected effects and should therefore be addressed as explanatory factors.

1.2. The Impact of Learner Prerequisites in AR-Based Learning Environments

Several meta-analyses have sought to explain the heterogeneous effects of AR studies by means of moderator analyses. However, only few of these included moderators related to learners' prerequisites. For example, some meta-analyses explored the impact of learners' individual educational level on the effectiveness of AR. The results are not consistent. While AR was found to be equally beneficial for different levels of education in some meta-analyses [4,34], others suggest that the learners' educational level can significantly impact the effect of AR on academic success [35] and motivation [36]. These mixed results may also reflect the varying effects of AR across different learning content. Consequently, some more content-related cognitive learner prerequisites should also be considered.

Throughout AR-supported lab work, learners encounter hybrid MERs consisting of verbal (e.g., the measurement values of current) or pictorial (e.g., experimental components) representations [19]. Against the background of capacity-limited dual channels for processing verbal and pictorial information [19,20], visuospatial abilities and verbal working memory capacity can thus be considered as particularly relevant learner prerequisites [5] for learning with hybrid MERs in lab work settings. Remarkably, despite the increasing prevalence of AR in educational research, these cognitive prerequisites have hardly been investigated in the context of learning with AR-based hybrid MERs [10,37].

1.2.1. The Role of Spatial Ability for Processing and Learning with (Hybrid) MERs

Spatial ability as a component of general cognitive ability is described as the capacity to "generate, retain, retrieve, and transform well-structured visual images" [38] (p. 98). It comprises five sub-factors [39], of which spatial visualization and spatial relations are the most investigated in the context of visuospatially enriched learning environments that require the understanding and manipulation of visual and spatial information. Since the factors of spatial ability are inextricably linked to visuospatial working memory [40,41], visuospatial working memory capacity can also be considered as a spatial ability measure [41,42].

Previous research has shown that spatial ability is positively related to learning outcomes in general [43] and to STEM learning outcomes in particular (e.g., [44]). Moreover, prior research revealed that especially high spatial ability learners benefit from classical multimedia learning settings providing combinations of text and pictures (e.g., in science education; [45]). They are assumed to process integrated verbal and pictorial learning information more effectively and thus to be able to use the resulting extra cognitive resources for the construction of referential connections between representations [5,46,47]. Consequently, high spatial ability learners are expected to profit from more elaborated mental models. In line with this, in a review, Cromley [48] found mean correlations from .20 to .40 for the relationship between spatial skills and different types of multimedia learning outcomes.

Further, the majority of research supports the assumption that spatial ability moderates learning in *spatially enriched* multimedia learning environments providing dynamic animations or 3D visualizations instead of static 2D visualizations. Nevertheless, the evidence supports opposing hypotheses on this moderation [43]: The ability-as-enhancer hypothesis [47] suggests that learners with high spatial ability profit most from spatial visualizations (e.g., [49,50]) as they are equipped with the necessary cognitive resources to manage the additional visuospatial load and successfully construct mental models. Learners with low spatial abilities, however, should experience particularly high cognitive load levels and have difficulties synthesizing the individual representations of MERs into a coherent mental model [51].

In contrast, the ability-as-compensator hypothesis [52] states that learners with high spatial abilities are able to compensate for lacking explicit spatial visualizations, while spatially weak learners struggle to construct a correct mental model themselves and therefore benefit most from explicit external visuospatial support (e.g., [53,54]).

In his meta-analytic review, Höffler [43] found evidence supporting the ability-as-compensator hypothesis. This hypothesis might be especially applicable for rather simple visuospatial enrichments that do not overload low spatial learners' working memory resources but spare their resources through simplifying integrated mental model construction. Kühl et al. [42] attempted to reconcile the opposing hypotheses, proposing that their applicability depends on the ability range of the learners under investigation. They suggested that medium abilities can enhance the benefits of spatial visualizations compared to low-ability learners who are unable to take advantage of spatial information. At the same time, very high abilities can compensate for lacking spatial information, resulting in medium ability learners gaining the most benefit from external spatial enrichment.

Spatiality is considered an important characteristic of AR experiences [6,55]. Virtual visualizations in AR can adapt dynamically to real-world changes and are perceived as spatially integrated into a 3D real world. Although AR learning setups can therefore be counted among spatially enriched learning environments, the moderating effect of spatial abilities on learning outcomes in AR has barely been investigated to date [34,37,56,57]. So far, empirical evidence has shown that AR can be a valuable tool to train spatial ability (e.g., [58–60]) and foster spatial thinking [61], which highlights the interdependency of AR and spatial ability. Moreover, Habig [37] investigated the influence of sex-related visuospatial differences for AR-supported chemistry learning. In their study, males and females performed a test on stereochemistry with half of the tasks using 2D figures to display chemical structures and the other half using tablet-based AR representations incorporating rotatable 3D models of chemical structures. They found that males were more likely to solve AR problems correctly, while females performed better in conventional 2D tasks. Their results support the ability-as-enhancer hypothesis, indicating that the required cognitive processes in the visuospatially enriched AR environment might have been hard to perform for students with lower spatial abilities, such as females. Krüger et al. [57] compared 3D and 2D AR representations of the human heart and found that 3D AR visualizations were superior in promoting GCL and spatial knowledge acquisition. Their study also supports the ability-as-enhancer hypothesis, suggesting that learners with higher spatial abilities profited most from 3D visualizations. Given the limited amount of research and the apparent relationship between AR and spatial abilities, Cheng and Tsai [56], in their review on suggestions for future research on AR in science learning, emphasized the need for investigating the impact of individual differences in mental spatial processing on the learning experience, process, and performance in AR.

1.2.2. The Role of Verbal Working Memory for Processing and Learning with (Hybrid) MERs

Verbal working memory refers to the mental maintenance of verbal (i.e., textual or numerical) information, and its capacity can affect the processing of verbal information. In contrast to findings on spatial abilities, the empirical evidence concerning the role of verbal working memory for learning with MERs is rather sparse. Nevertheless, verbal and numerical working memory capacity is also assumed to affect multimedia learning outcomes ([5,62]; for a review, see [63]). For example, Pazzaglia et al. [64] investigated a hypermedia learning environment for children and found both visuospatial and verbal working memory influencing the processing of multimedia material. In particular, they observed verbal memory capacity to be positively related to the acquisition of semantic knowledge. The results of Plass et al.'s [65] study on language learning with MERs underscore the relevance of visuospatial and verbal abilities, with verbal ability being assumed to be particularly helpful under high-load multimedia conditions. In their study, verbal ability was assessed with a vocabulary speed test, which has been shown to be highly correlated with verbal working memory capacity. Studies using a dual-task methodology further support the presumption that verbal working memory is involved in text processing during multimedia learning [66]. Moreover, prior research demonstrated that learners with low verbal working memory capacity suffered most from split attention between representations but also suggested that integrative instructional design can compensate for working memory deficits [67].

In the context of hybrid MERs in AR-supported lab work environments, the processing of verbal information is of crucial importance. Experimental setups often include verbal instructions, hints, or explanations that guide the learning process. Moreover, measurement values as numerical information that is also processed in the verbal working memory channel play a central role in science experiments. They must be linked to physical phenomena to make them quantifiable, analyzable, and understandable.

1.3. Present Study and Hypotheses

This present research aims to uncover the possible moderating effects of spatial abilities and verbal working memory capacity in three studies on AR-supported lab work environments on electricity education. Re-analyses to detect the potential moderators on the effects of AR support on ECL and conceptual knowledge gains may help to explain and reconcile the ambiguous results. The inconsistency of AR effects across the three studies may be attributed to aptitude-treatment interactions. The studies were collaboratively conceptualized by various disciplines, each integrating their specific research questions. As a result, each study typically investigated not only technological and pedagogical research questions but also methodological issues related to measurements. Consequently, they included multiple measures for assessing learning outcomes, cognitive load, and learner prerequisites.

As ECL was measured with two separate cognitive load scales in Study 1 [1] and Study 2 [17], convergent and discriminant moderator effects, depending on the scale, will be discussed. Further, conclusions will be drawn to expand the theoretical presumptions on learning with hybrid MERs in AR-supported lab work settings by addressing the impact of interindividual differences regarding spatial and verbal processing.

Hypotheses 1a and 1b explore how individual differences in spatial processing influence the effect of AR-induced hybrid MERs on ECL and learning outcomes in a lab work setup. Who benefits most from spatial enrichment is assumed to depend on the requirements of the learning material [43] and learners' spatial ability range [42]. Since integrated virtual measurement values provide a rather simple visuospatial enrichment, we do not expect them to cognitively overload but to relieve the ECL of low spatial learners.

Hypothesis 1a. Spatial ability moderates the effect of the presentation format (AR vs. separate display) on ECL. The instructional reduction of split attention is expected to show particularly strong diminishing effects on ECL in learners with low spatial abilities.

Learning outcomes, such as conceptual knowledge gains, are assumed to be closely related to self-rated cognitive load levels and can also indicate split attention effects. Moreover, they can capture aspects of load that cannot be assessed by retrospective subjective rating scales. Therefore, we additionally investigated the moderating role of spatial abilities for the effect of AR on conceptual knowledge gains.

Hypothesis 1b. Spatial ability moderates the effect of the presentation format on learning outcomes. The instructional reduction of split attention is expected to be particularly beneficial for learning outcomes in learners with low spatial abilities.

Hypotheses 2a and 2b address the moderating effect of verbal working memory capacity. It is assumed that learners with particularly high verbal working memory capacity are able to encode and store larger units of verbal information between glances [24]. However, for learners with low verbal working memory capacity, integrated MERs can faciliate resource-consuming mental search processes that are necessary for coherence formation. This should be reflected in lower ECL levels.

Hypothesis 2a. Verbal working memory capacity moderates the effect of the presentation format on ECL. The instructional reduction in split attention is expected to show particularly strong diminishing effects on ECL in learners with low verbal working memory capacity.

The instructional reduction of split attention effects and the facilitation of mental search processes should also free mental capacities for meaningful learning, which should lead to improved learning outcomes. Further, learning outcomes can reflect additional aspects beyond self-rated cognitive load. Consequently, we also investigated the moderating role of verbal working memory capacity for the effect of AR on conceptual knowledge gains.

Hypothesis 2b. Verbal working memory capacity moderates the effect of the presentation format on learning outcomes. The instructional reduction of split attention is expected to be particularly beneficial for learning outcomes in learners with low verbal working memory capacity.

2. Materials and Methods

2.1. Study Samples

All the three studies to be re-analyzed applied a pretest–posttest design to compare an AR-supported with a separate display lab work setting on electrical circuits regarding ECL levels and learning outcomes in terms of conceptual knowledge gains. In the first study under investigation [1], N = 50 (80% female) university students were assigned to a separate display condition or a tablet-based AR environment (age: M = 25.98; SD = 4.67). While the vast majority of students were accustomed to using smartphones and tablets regularly, most of them reported being unfamiliar with AR. The valid sample of the second study [17] consisted of N = 107 engineering students (14% female, age: M = 19.05; SD = 5.20) working with separate displays or smartglasses-based AR. In the third study examining tablet-based AR for elementary school students [18], N = 114 children took part (47% female, age: M = 9.06, SD = 0.87). In none of the studies did the participants have any domain-specific prior knowledge about electricity that went beyond what they had learned about it at school. Furthermore, in none of the studies were the participants known to have cognitive impairments. However, this cannot be completely ruled out as it was not explicitly asked about. It should further be noted that the samples may not be representative of the respective age groups due to selection bias. University students and children participating in scientific studies are likely to have a higher-than-average level of education. Due to time constraints in the three studies, the sample sizes for certain moderator variables were reduced. Some participants took longer than expected to complete the lab work phase and therefore were unable to complete some of the cognitive tests at the end of the investigation. An overview of the three studies, including the instruments used and corresponding sample sizes, can be found in Table 1.

Table 1. Summary of re-analyzed studies.

Study	Sample	Presentation Format (n)	Spatial Ability Tests (n)	Verbal Working Memory Tests (n)
Study 1 [1]	Mixed university students	Separate tablet display (25)	Paper folding test (25) Card rotation test (25) Visual pattern tests (16)	Visual digit span test (25)
		Handheld tablet AR (25)	Paper folding test (25) Card rotation test (25) Visual pattern test (20)	Visual digit span test (25)
Study 2 [17]	Engineering university students	Separate tablet display (58)	Paper folding test (55) Card rotation test (53) Visual pattern tests (55)	Visual digit span test (40)
		Smartglasses (49)	Paper folding test (39) Card rotation test (38) Visual pattern tests (43)	Visual digit span test (29)
Study 3 [18]	Elementary school students	Separate tablet display (56)	Spatial relations test (54)	Visual digit span test (47)
		Fixed tablet AR (58)	Spatial relations test (58)	Visual digit span test (49)

2.2. Procedures and Measures of Cognitive Load, Conceptual Knowledge, Spatial Ability, and Verbal Working Memory Capacity

The three studies followed the same workflow, which is depicted in Figure 1.

After an introduction to the topic of electricity, the subjects were provided with a pretest on their conceptual understanding of electrical circuits (adapted from [68,69]; see [1,17,18] for exemplary items). The subjects were then randomly assigned to the AR-supported or the separate display condition. Subsequently, the participants familiarized themselves with the technology and were then guided through a series of experiments dealing with serial and parallel electrical circuits. In every experiment, the subjects first built up an electrical circuit. While university students worked with resistors, elementary students used light bulbs instead. For every experiment, voltage was then applied on the circuit and manipulated at the power supply. The subjects observed and compared measured values of voltage only [18] or of voltage and amperage [1,17] for different circuit components. During the experimentation, the participants answered questions on the relations of the measured values. The virtual measurement values were displayed above the corresponding components for the AR-supported conditions. The separate display condition was provided with a matrix of measurement values on a tablet (see Figure 2). For the study on elementary students [18], gaze data were recorded during lab work. After the lab work phase, cognitive load was assessed via subjective rating scales. Study 1 [1] and Study 2 [17] used adapted versions of Leppink et al.'s [29] scale translated to German, as well as an adapted version of Klepsch et al.'s [27] German scales to assess ICL, ECL, and GCL. The third study [18] provided a cognitive load questionnaire for ICL and ECL particularly tailored to the needs of elementary school children [70]. Afterwards, the students completed the test on conceptual knowledge for a second time, and, depending on the study, some more specific posttests.

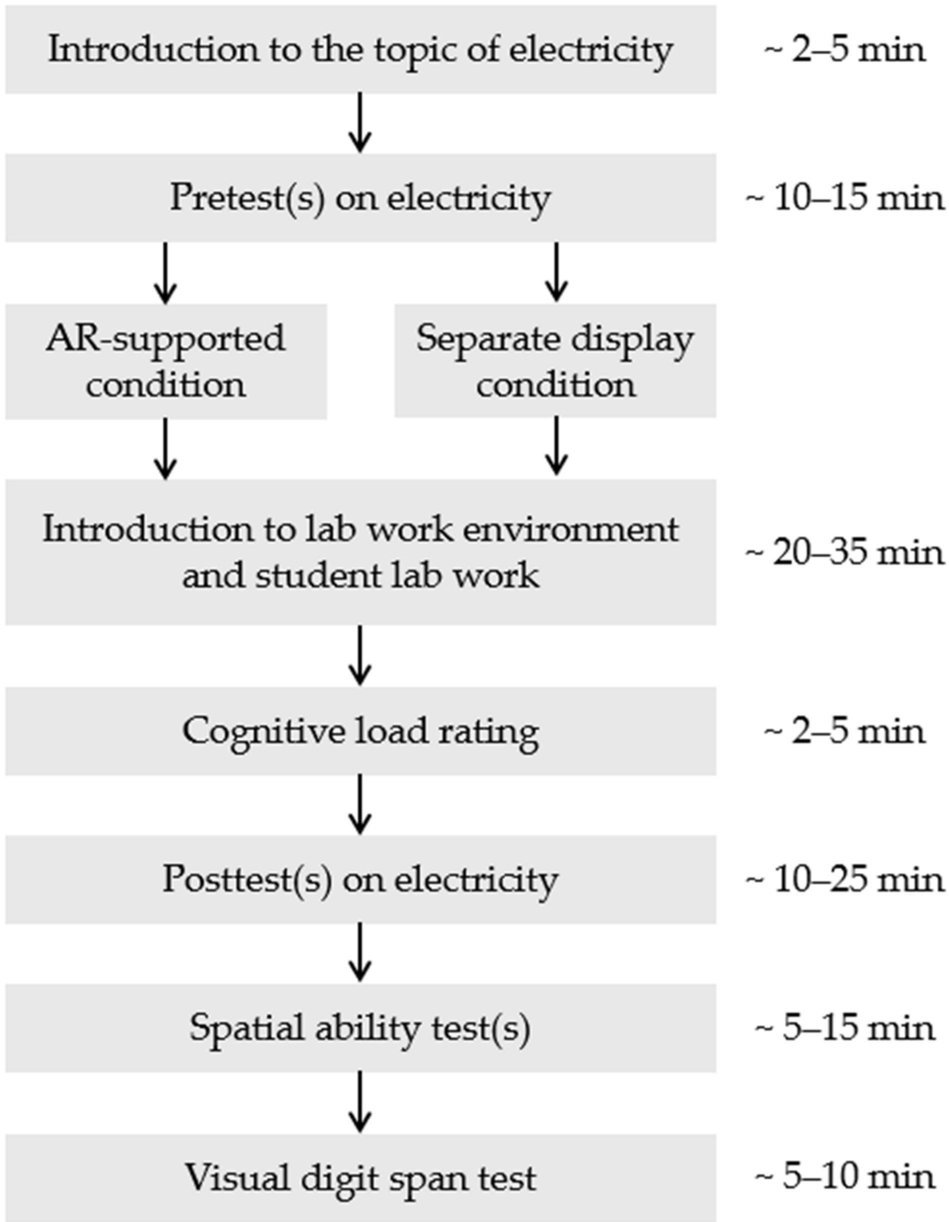

Figure 1. Workflow and time specifications of the three studies to be re-analyzed for moderating variables. Particularly for Study 3 investigating a sample of children, the time required for the single parts of the study varied significantly between the individuals.

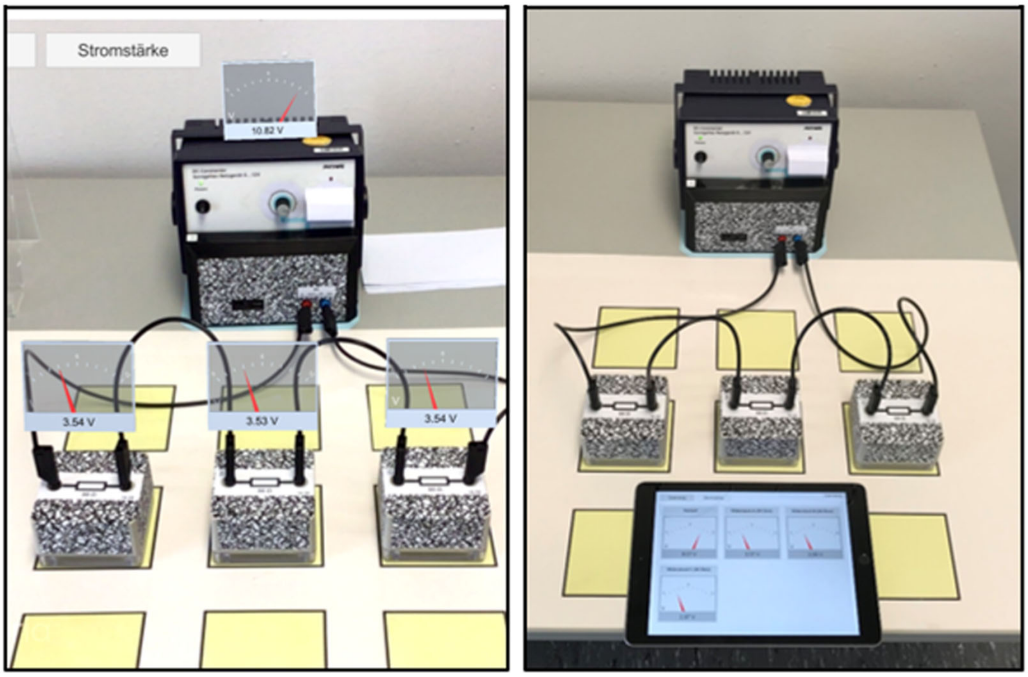

Figure 2. Left: AR-supported learning environment with measurement data virtually integrated into the experimental setup by smartglasses or tablet cameras. **Right**: separate display learning environment with measurement data provided grouped together on an external tablet.

Having completed the posttests on electricity, three spatial ability tests were performed for the samples of university students. The paper folding test measured the spatial visualization factor and the card rotation test measured the spatial relations factor [71]. Both tests capture the ability to mentally transform objects, e.g., by rotation or inversion [41]. However, the card rotation test is constructed of less complex 2D items and has to be completed faster [40]. The visual pattern test [72] was used to measure the visual component of visuospatial memory in the samples of university students. The test covers the recall performance of two-dimensional patterns arranged in matrices. In the study on elementary school children, spatial ability was assessed by means of the spatial relations subtest of the Primary Mental Abilities Tests Battery by Thurstone and Thurstone [73], which is a common instrument for children of elementary school age. Subsequently, verbal working memory capacity was captured by visual digit span tests. The university students had to recall sequences of four to thirteen digits [71]. The elementary school students completed an adaptive visual digit span test with tasks of increasing difficulty (a visual adaption of the "Repeating Numbers" test of the WISC-V; [74]). Finally, all the participants gave demographic information.

3. Results

3.1. Descriptive Statistics

Table 2 describes the score calculation for dependent and moderator variables. It takes into account the benefit of guessing in speed tests (concerning the paper folding and card rotation tests).

Table 2. Score calculations and maximum scores for dependent and moderator variables.

Variable	Score Calculation	Maximum
Conceptual knowledge gain	Difference between the number of correctly solved tasks in the posttest and the pretest	13 [1], 10 [2], 11 [3]
ECL	Mean of ECL item responses	7 [1,2], 5 [3]

Table 2. *Cont.*

Variable	Score Calculation	Maximum
Paper folding test	Number of correctly solved tasks minus one-fifth the number of incorrect tasks in 3 min	10 [1,2]
Card rotation test	Number of correctly solved tasks minus the number of incorrect tasks in 3 min	80 [1,2]
Visual pattern test	Mean of the complexity indices of the last three correctly recalled patterns	15 [1,2]
Spatial relations test	Number of correctly solved tasks	16 [3]
Visual digit span test	Mean of the last three correctly recalled digit sequence lengths	12.33 [1,2], 9.66 [3]

[1] Study 1 [1]; [2] Study 2 [17]; [3] Study 3 [18].

The descriptive statistics for conceptual knowledge gain, ECL, and moderator variables are displayed in Tables 3 and 4, separately for each study.

Table 3. Means (*M*) and standard deviations (*SD*) of dependent and moderator variables for Study 1 [1] and Study 2 [17], separated by presentation format conditions.

	Study 1 [1]		Study 2 [17]	
	Separate Display	AR	Separate Display	AR
Conceptual knowledge gain	−0.28 (2.37)	0.84 (1.84)	0.09 (1.98)	0.00 (1.62)
ECL (Leppink et al. [29])	1.54 (0.51)	1.31 (0.49)	1.69 (0.46)	1.69 (0.56)
ECL (Klepsch et al. [27])	1.88 (0.94)	1.64 (0.87)	1.88 (0.82)	2.25 (0.99)
Paper folding test	5.82 (2.51)	5.62 (2.66)	5.87 (2.24)	6.14 (2.32)
Card rotation test	55.72 (15.99)	56.20 (13.00)	53.15 (21.06)	57.18 (21.66)
Visual pattern test	10.27 (1.38)	10.49 (1.99)	10.94 (1.64)	10.53 (1.75)
Visual digit span test	6.76 (1.00)	6.80 (1.32)	6.24 (1.49)	6.51 (0.84)

Table 4. Means (*M*) and standard deviations (*SD*) of dependent and moderator variables, for Study 3 [18], separated by presentation format conditions.

	Separate Display	AR
Conceptual knowledge gain	4.14 (2.56)	3.78 (2.36)
ECL	1.48 (0.50)	1.51 (0.53)
Spatial relations test	13.41 (1.85)	13.72 (1.83)
Visual digit span test	4.19 (0.67)	4.01 (0.78)

3.2. Assumptions and Preliminary Considerations for the Following Analyses

To re-analyze our three studies with the aim of identifying explanatory influences on the effects of AR, the PROCESS macro by Hayes [75] was used to perform several moderator analyses. Alongside the standard regression analyses yielding *p*-values, 5000 bootstraps were calculated for each analysis to generate and test for bias-corrected and accelerated 90% bootstrap confidence intervals (BCa 90% CI; one-tailed). A heteroscedasticity consistent standard error and covariance matrix estimator was selected (HC3, Davidson-McKinnon). Bootstrapping is a robust approach that generally makes no assumptions in terms of distribution characteristics, which is particularly relevant for rather small samples. It is still crucial to acknowledge that the limited sample sizes might diminish the statistical power of the analyses. Therefore, the following results must be interpreted with caution and the understanding that they only suggest potential trends.

3.3. Hypothesis 1a: The Moderating Role of Spatial Ability for the Effect of Presentation Format on ECL

Hypothesis 1 concerns the moderator variables of spatial ability. With regard to Hypothesis 1a, performance in the paper folding test acted as a marginally significant moderator (although not indicated by the BCa 90% CI) and performance in the card rotation test was a significant moderator (see Figure 3) for the effect of presentation format on ECL measured with Klepsch et al.'s [27] scale in Study 1 [1] (see Table 5). Subjects with low spatial abilities showed less ECL in the AR-supported condition compared to the separate display presentation format.

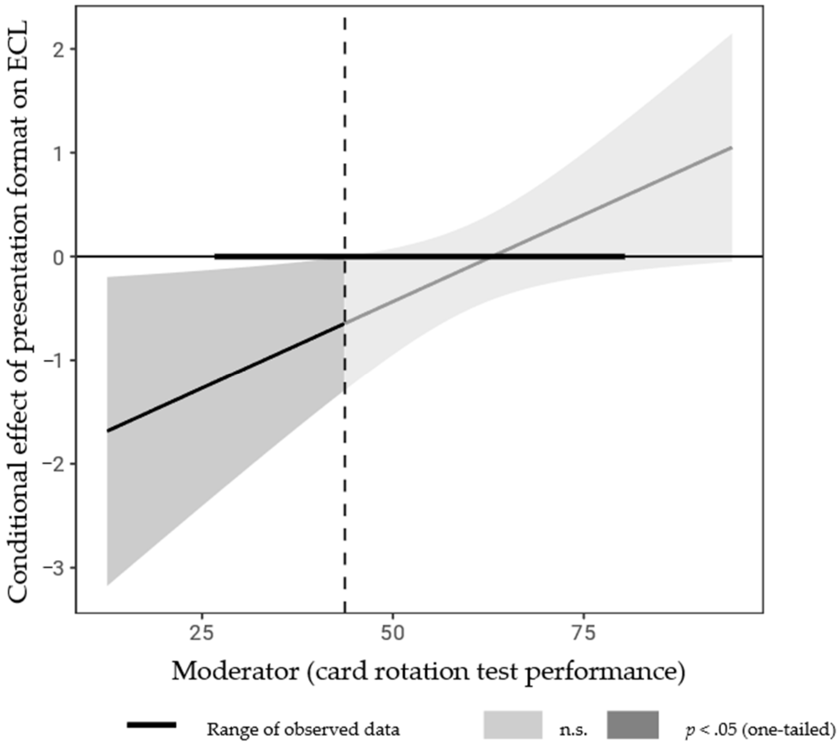

Figure 3. Johnson–Neyman plot illustrating the significant interaction between the presentation format (AR was coded as 1 and the separate display condition was coded as 0) and the moderator card rotation test performance for the dependent variable ECL [27] in Study 1.

Table 5. Moderator analyses for the effect of presentation format on ECL measured by adapted versions of Leppink et al.'s [29] and Klepsch et al.'s [27] scales in Study 1 [1].

	ECL (Leppink et al. [29])					ECL (Klepsch et al. [27])				
Moderator	***df***	***F***	***p***	**BCa 90% CI**	**ΔR^2**	***df***	***F***	***p***	**BCa 90% CI**	**ΔR^2**
Paper folding test	1/46	0.16	.344	[−0.071; 0.116]	.003	1/46	2.47	.061 †	[−0.012; 0.007]	.035
Card rotation test	1/46	0.01	.462	[−0.016; 0.018]	.000	1/46	4.49	.034 *	[0.003; 0.063]	.068
Visual pattern test	1/36	0.14	.358	[−0.263; 0.169]	.004	1/36	0.13	.358	[−0.260; 0.404]	.003
Visual digit span test	1/46	0.93	.169	[−0.386; 0.104]	.024	1/46	0.12	.365	[−0.079; 0.055]	.003

† $p < .10$, and * $p < .05$.

Neither in Study 2 [17] (see Table 6) nor in Study 3 [18] (see Table 7) were the spatial ability test performances identified as significant moderators with regard to the effect of the presentation format on ECL.

Table 6. Moderator analyses for the effect of presentation format on ECL, measured by adapted versions of Leppink et al.'s [29] and Klepsch et al.'s [27] scales in Study 2 [17].

	ECL (Leppink et al. [29])					ECL (Klepsch et al. [27])				
Moderator	*df*	*F*	*p*	**BCa 90% CI**	ΔR^2	*df*	*F*	*p*	**BCa 90% CI**	ΔR^2
Paper folding test	1/90	0.46	.249	[−0.002; 0.002]	.004	1/90	0.97	.163	[−0.217; 0.055]	.011
Card rotation test	1/87	0.49	.245	[−0.013; 0.005]	.007	1/87	0.91	.171	[−0.026; 0.007]	.013
Visual pattern test	1/94	0.04	.422	[−0.097; 0.123]	.001	1/94	0.00	.479	[−0.218; 0.205]	.000
Visual digit span test	1/65	0.36	.276	[−0.336; 0.159]	.007	1/65	3.29	.037 *	[−0.726; −0.030]	.045

* $p < .05$.

Table 7. Moderator analyses for the effect of presentation format on ECL measured by an adapted version of Altmeyer et al.'s [70] scale for elementary school children in Study 3 [18].

Moderator	*df*	*F*	*p*	**BCa 90% CI**	ΔR^2
Spatial relations test	1/108	0.08	.392	[−0.075; 0.105]	.001
Visual digit span test	1/92	1.70	.098 †	[−0.055; 0.457]	.020

† $p < .10$.

3.4. Hypothesis 1b: The Moderating Role of Spatial Ability for the Effect of Presentation Format on Conceptual Knowledge Gain

The results for Hypothesis 1b showed no significant moderation effect of spatial ability for the effect of presentation format on conceptual knowledge gain for all three studies. Tables 8–10 illustrate the statistics on the moderator effects.

Table 8. Moderator analyses for the effect of presentation format on conceptual knowledge gain for Study 1 [1].

Moderator	*df*	*F*	*p*	**BCa 90% CI**	ΔR^2
Paper folding test	1/46	1.18	.141	[−0.498; 0.107]	.013
Card rotation test	1/46	0.30	.293	[−0.045; 0.090]	.005
Visual pattern test	1/36	0.08	.388	[−0.467; 0.256]	.003
Visual digit span test	1/46	0.01	.462	[−1.209; 1.078]	.000

Table 9. Moderator analyses for the effect of presentation format on conceptual knowledge gain for Study 2 [17].

Moderator	*df*	*F*	*p*	**BCa 90% CI**	ΔR^2
Paper folding test	1/90	0.17	.342	[−0.200; 0.330]	.002
Card rotation test	1/87	0.19	.331	[−0.033; 0.019]	.002
Visual pattern test	1/94	1.13	.146	[−0.613; 0.135]	.012
Visual digit span test	1/65	0.60	.221	[−0.489; 1.331]	.013

Table 10. Moderator analyses for the effect of presentation format on conceptual knowledge gain for data of Study 3 [18].

Moderator	*df*	*F*	*p*	BCa 90% CI	ΔR^2
Spatial relations test	1/108	0.00	.492	[−0.410; 0.400]	.000
Visual digit span test	1/92	0.44	.254	[−1.667; 0.714]	.005

3.5. Hypothesis 2a: The Moderating Role of Verbal Working Memory Capacity for the Effect of Presentation Format on ECL

Hypothesis 2 investigates the role of verbal working memory. The moderator analyses for Hypothesis 2a revealed no significant moderation effect of verbal working memory in Study 1 [1] (see Table 5). In Study 3 [18], there was a marginally significant moderator (which was not indicated by the BCa 90% CI), indicating that children scoring high in verbal working memory report less ECL in the separate display condition (see Table 7). In Study 2 [17], performance in the digit span test acted as a significant moderator for the effect of the presentation format on ECL, measured with Klepsch et al.'s [27] scale (see Table 6). In this study, subjects scoring low in verbal working memory reported less ECL for the separate display compared to the smartglasses AR-supported experimentation environment (see Figure 4).

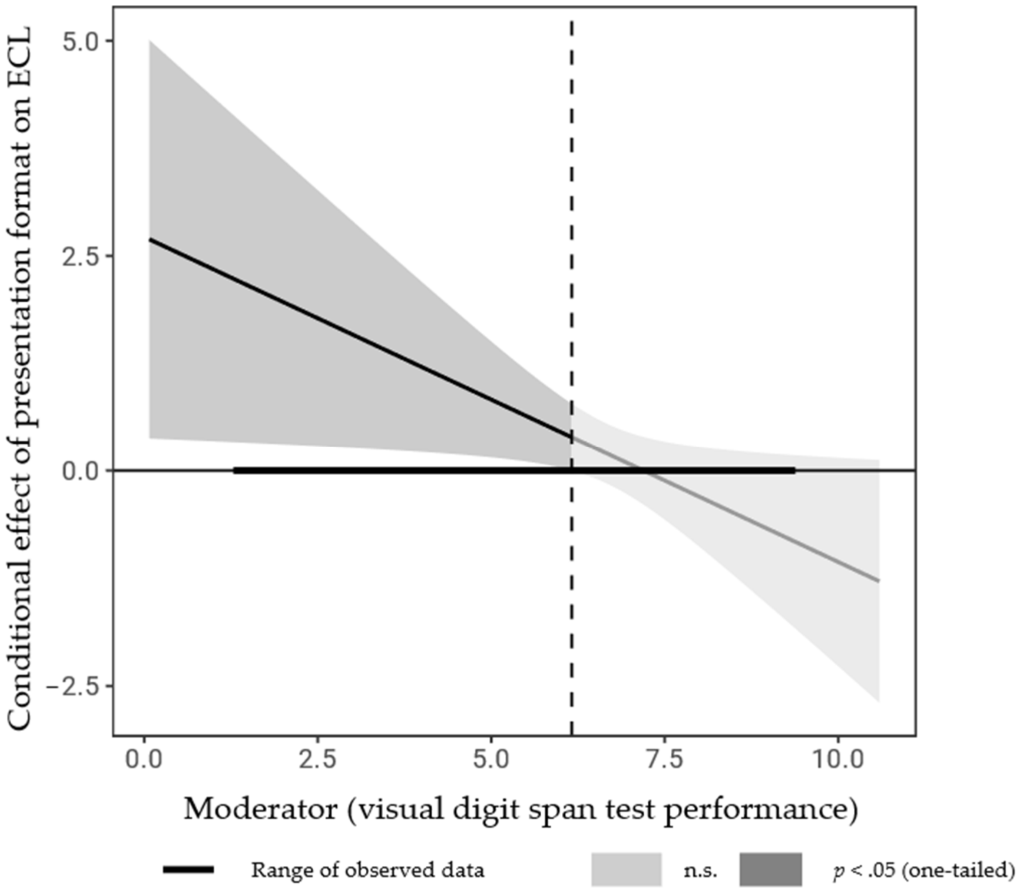

Figure 4. Johnson–Neyman plot illustrating the significant interaction between the presentation format (AR was coded as 1 and the separate display condition was coded as 0) and the moderator visual digit span test performance for the dependent variable ECL [27] in Study 2.

3.6. Hypothesis 2b: The Moderating Role of Verbal Working Memory Capacity for the Effect of Presentation Format on Conceptual Knowledge Gain

Concerning Hypothesis 3b, verbal working memory was no significant moderator for the effect of presentation format on conceptual knowledge gains in any study (see Tables 8–10).

3.7. Exploratory Results

The relationships between dependent variables and moderators across the participants of both conditions (separate display and AR-supported) were investigated in an explorative manner for each study (see Tables 11–13).

Table 11. Bivariate correlations (two-tailed) between variables of Study 1 [1].

	CKG		ECL [29]		ECL [27]		PFT		CRT		VPT	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Conceptual knowledge gain (CKG)												
ECL (Leppink et al. [29])	−.10	.510										
ECL (Klepsch et al. [27])	−.06	.705	.48	<.001 **								
Paper folding test (PFT)	.16	.261	.09	.543	−.13	.368						
Card rotation test (CRT)	−.07	.656	−.10	.486	−.23	.113	.25	.085 †				
Visual pattern test (VPT)	.25	.114	−.14	.395	−.32	.045 *	.43	.005 *	.13	.434		
Visual digit span test	.04	.777	−.11	.464	−.33	.018 *	−.02	.882	.16	.274	.32	.047 *

† $p < .10$; * $p < .05$; and ** $p < .01$.

Table 12. Bivariate correlations (two-tailed) between variables of Study 2 [17].

	CKG		ECL [29]		ECL [27]		PFT		CRT		VPT	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Conceptual knowledge gain (CKG)												
ECL (Leppink et al. [29])	−.11	.260										
ECL (Klepsch et al. [27])	−.05	.592	.55	<.001 **								
Paper folding test (PFT)	.17	.105	.10	.320	−.04	.673						
Card rotation test (CRT)	.02	.880	−.07	.504	−.16	.133	.33	.001 **				
Visual pattern test (VPT)	.21	.034 *	−.10	.351	−.20	.045 *	.27	.009 **	−.00	.982		
Visual digit span test	.04	.749	.07	.551	−.09	.472	.17	.172	.22	.066 †	.16	.197

† $p < .10$; * $p < .05$; and ** $p < .01$.

Table 13. Bivariate correlations (two-tailed) between variables of Study 3 [18].

	CKG		ECL		SRT	
	p	*r*	*p*	*r*	*p*	*r*
Conceptual knowledge gain (CKG)						
ECL	−.05	.592				
Spatial relations test (SRT)	.01	.907	−.09	.350		
Visual digit span test	.21	.039 *	−.28	.006 **	.16	.132

* $p < .05$; and ** $p < .01$.

For Study 3 [18], correlations between learner prerequisites and mean number of transitions between different representations that were captured by eye tracking during lab work were exploratively investigated. The statistics are displayed in Table 14.

Table 14. Bivariate correlations (two-tailed) between eye tracking variables and moderator variables of Study 3 [18].

		Spatial Relations Test		Visual Digit Span Test	
		r	*p*	*r*	*p*
Mean number of transitions within single circuits	Circuit ↔ tablet	.03	.852	.19	.229
	Workbook ↔ tablet	−.29	.046 *	−.18	.256
	Workbook ↔ circuit	−.24	.094 †	−.03	.870
Mean number of transitions between two circuits	Tablet ↔ tablet	.30	.037 *	.06	.692
	Circuit ↔ circuit	−.12	.428	−.01	.956

† $p < .10$; and * $p < .05$.

4. Discussion

This present research re-analyzed three recent studies to investigate the moderating role of learners' spatial ability and verbal working memory capacity for the effect of AR support on ECL and conceptual knowledge gains in lab work environments. The three related studies under investigation shared similar lab work setups and workflows but differed in terms of the sample characteristics and AR devices used. While the expected moderators could not be confirmed across all studies, the re-analyses revealed that tablet-based AR reduced ECL compared to a separate display condition among university students with particularly low spatial abilities [1]. In contrast, smartglasses-based AR induced more ECL than the separate display condition in university students with low verbal memory capacity [17]. No significant moderators were found for the effect of AR support on conceptual knowledge. In summary, the findings of the re-analyses point out that the mental processing benefits gained from AR support during lab work may depend on learners' individual cognitive prerequisites. The varying relevance of spatial and verbal learner prerequisites across the three studies underscores the interdependence of these learner-centered moderator variables with further contextual factors, such as the particular AR device used and age of the target group.

4.1. The Moderating Role of Spatial Ability

Hypothesis 1a could be confirmed for Study 1 [1] as the performance in the paper folding and card rotation spatial ability tests acted as (marginally) significant moderators for the effect of presentation format on self-rated ECL. In a sample of university students, learners with low spatial abilities reported less ECL (measured with Klepsch et al.'s [27] scale) in the tablet-based AR condition than in the separate display condition. While the original research only showed significant differences between the conditions in conceptual knowledge acquisition, the moderator analysis thus suggests that AR may also impact ECL in certain subjects. The results are in line with the ability-as-compensator hypothesis [52,53], suggesting that the spatial enrichment through AR relieved the working memory of spatially weak learners. While prior studies on spatial enhancement in or through AR [37,57] found evidence for the ability-as-enhancer hypothesis, the current support for the ability-as-compensator hypothesis may be explained by the rather simple visuospatially integrated measurement values that did not overload low spatial learners' working memory resources but supported their mental integration processes [22]. The ability range of the participants further contributes to the manifestation of the ability-as-compensator hypothesis [42]. Given the selection bias in the sample of university students, even those learners considered as spatially weaker may still possess sufficient visuospatial abilities to benefit from the external spatial enrichment provided. Tablet-based AR may have served as a "cognitive prosthetic" [76] for low spatial learners. The spatial and temporal contiguity [21] created by AR probably supported low spatial learners in the formation of mental interrelations between the experimental setup and measurement data, thereby reducing ECL. In the other two studies, spatial ability was not identified as a significant moderator. With regard to Study 2 [17] on smartglasses AR-supported lab work, the spatial contiguity failure [32] caused by the technically limited field of view of smartglasses AR could have offset the positive effects of AR, regardless of the individual spatial prerequisites. The ECL of elementary school students using tablet-based AR in Study 3 [18] was also not significantly affected by spatial learner prerequisites. The lack of significant effects in Study 3 [18] could be due to the fact that individual spatial abilities are still developing at elementary school age and may therefore have less explanatory power in this age group.

Contrary to Hypothesis 1b, spatial ability did not significantly influence the effect of the presentation format on conceptual knowledge gains in any study. Although prior research shows that ECL and learning outcomes are related, ECL seemed to be the more sensitive for spatial moderator effects in Study 1 [1].

4.2. The Moderating Role of Verbal Working Memory Capacity

With regard to Hypothesis 2a, the re-analysis of Study 2 [17] implies that, for low verbal working memory learners, using smartglasses AR induced more ECL than using a separate display to observe measurement values. This is in line with Thees et al.'s [17] assumption that the limited field of view of smartglasses broke up coherent structures between measurement values and thereby disrupted coherence formation processes [32]. Thus, the referential connections between measured values augmented by means of smartglasses required a lot of working memory resources. While high verbal working memory learners seemed to be able to keep larger units of measurement digits in their working memory and could thereby compensate for the spatial fragmentation, particularly high ECL was caused in learners with low verbal working memory capacity. The current re-analysis confirms the findings of Study 2 [17] that smartglasses AR can indeed impede certain cognitive matching processes. However, it extends and refines these conclusions by taking into account the dependence of the effects on individual learner prerequisites: The segmentation of measurement values by smartglasses may not be generally obstructive but seems to specifically challenge learners with lower working memory capacity. In contrast, the tablet-based AR used in Study 1 [1] and Study 3 [18] allowed students to view all measurement values simultaneously. This was also the case for the separate display conditions that saw the measurement values grouped together in a grid. Thus, memorizing and comparing measurement values was equally demanding in both conditions. This might explain why verbal working memory capacity showed no significant moderating effect in any of the tablet-based AR studies. Nevertheless, a marginal significant moderating effect for Study 3 [18] (though not reflected in the 90% BCa CI and requiring cautious interpretation) suggests that, for learners with high verbal working memory capacity, AR might have induced higher levels of ECL compared to the separate display condition. According to the ability-as-compensator hypothesis, high working memory learners may not benefit as much from AR, since they can manage split-source material without integrative AR support. However, AR can pose additional technological challenges, particularly for younger participants. For instance, adjusting the tablet to maintain the visibility of the markers and keeping the measurement values in view can be difficult. As a result, AR may have acted as a distraction rather than a support for children. Especially since children's inhibitory control is still developing, AR could have made it harder for them to focus on the learning task. These distractions likely contributed to higher ECL, making the separate display format more effective in reducing extraneous processing for children with sufficient verbal working memory capacity to manage split attention between information sources.

Similar to the results on spatial ability, the re-analyses did not find verbal working memory capacity to significantly moderate the effect of presentation format on conceptual knowledge gains in any study (Hypothesis 2b). ECL, as a measure closer to actual learning processes, seems to be a more sensible dependent variable for moderator effects of cognitive learner prerequisites than conceptual knowledge gains in Study 2 [17].

4.3. Further Findings and Considerations

The explorative results on the relationship between potential moderators and dependent variables across conditions revealed that spatial ability tests are related but nevertheless capture different aspects of spatial ability [40]. For every study, the performance in the digit span test was negatively related to ECL, which confirms that the ECL measurements are related to working memory load [25]. For Study 1 [1], the exploratory results additionally showed a negative relationship between visuospatial working memory and ECL. Conceptual knowledge gain was positively related to visuospatial working memory in Study 2 [17] and digit span performance in Study 3 [18]. This points to the assumed link between cognitive prerequisites and learning outcomes [43,63] and also indicates that both may be influenced by a general intelligence factor.

Study 1 [1] and Study 2 [17] both used two different scales to assess the dimensions of cognitive load. Remarkably, although the ECL measures showed highly significant correlations in both studies, the moderation effects and meaningful correlations only manifested in Klepsch et al.'s [27] scale. This clearly highlights the fact that cognitive load questionnaires vary in their assessed load aspects [28] and that some scales seem to be more sensitive to specific group differences and moderator effects than others. Future studies should therefore choose the load scale carefully, match it precisely to the objectives of the study, and combine different cognitive load measurement approaches to examine convergent validity aspects.

The exploratory results on transitions between representations captured in Study 3 [18] indicate that subjects with high spatial abilities needed to perform fewer transitions between workbook and tablet, as well as between workbook and circuit, within single circuits. In contrast, the higher the spatial ability performance, the more transitions between the tablets of two experimental setups were performed. These results underscore that spatial ability clearly influences the processing of MERs in lab work setups. To deepen our understanding of how individual learner differences impact information processing, promising process measures like gaze behavior should be further investigated.

4.4. Limitations and Future Research

The first limitation of the present re-analysis concerns the sample sizes and compositions of the samples. Regression-based approaches require large samples to ensure adequate statistical power. Consequently, as with many behavioral regression studies, the samples of the present re-analyses must be considered statistically underpowered [77,78]. The findings should therefore be interpreted as indicative of possible trends rather than as definitive conclusions. However, despite this limitation, this study provides valuable insights into the role of cognitive learner prerequisites for the effectiveness of AR support in lab work environments, particularly given the paucity of research in this area. The present results can further be included in future meta-regressions to achieve sufficient power and precision [77,79] and can stimulate future research.

Further, the homogeneity of the samples consisting of university students and selected children regarding general cognitive ability and thus spatial and verbal competencies might have impeded the investigation of the moderator variables. Kühl et al. [42] suggest that the specific manifestation of spatial ability as a moderator variable depends on the ability range of the learners under investigation. Against this background, it is all the more important to examine the full and representative range of cognitive abilities to draw reliable conclusions about their influences.

Moreover, the gender distribution in the re-analyzed studies was uneven, particularly among university students. While the sample of Study 1 [1] mainly consisted of female subjects (80%), men predominated in Study 2 [17] (86%). Research has shown that gender is related to spatial ability and even impacts multimedia outcomes when results are controlled for spatial ability [80]. Consequently, the differences between the studies cannot be related exclusively to differences in experimental design (e.g., the use of smartglasses vs. tablet-based AR), but may also reflect the impact of imbalances in sample distribution. Habig [37] has identified sex differences in AR-supported chemistry learning tasks, theoretically attributing these disparities to variations in visuospatial abilities between genders. Future research should investigate and align both cognitive prerequisites and gender to better understand their interrelated influences.

A further limitation is that the learning tasks may have been too easy for the target groups, potentially reducing the effects of AR and masking the interaction effects. This limitation might explain why the cognitive variables did not moderate the effect of the presentation format on conceptual knowledge gains. Future research should explore the moderators of learning outcomes in AR-supported environments using diverse samples and more challenging tasks across various domains. This approach would also enhance the generalizability of the findings.

The retrospective self-assessment of cognitive load depicts another drawback of this present research. Retrospective cognitive load self-assessment is biased by a lack of objectivity and direct temporal connection to the learning process [70]. In future studies, objective, physiological, or behavioral online measurements (e.g., smartpen measures, [70]) could additionally be considered and combined with traditional questionnaires to achieve more reliable, multimodal cognitive load measurements. Moreover, the studies showed floor effects in cognitive load ratings. This constraint of variance may have covered potential moderation effects. Another cognitive load-related limitation is described in Schroeder and Cenkci's [81] review, which revealed missing evidence for differences in ECL between integrated and spatially distant designs. They argued that the positive effects of integrated learning environments might rather result from a beneficial allocation of germane resources. Consequently, future studies should also examine the moderating role of learner prerequisites for the effect of AR on GCL.

An additional constraint is that cognitive prerequisites were assessed after the intervention for all studies. Since the use of AR applications has been shown to have positive effects on a user's spatial ability [59–61], it is possible that the AR interventions in the re-analyzed studies may have influenced subjects' spatial abilities. However, this can be considered a minor constraint since the AR learning environments of the present studies did not meet the conditions of an AR-based spatial ability training (e.g., the possibility to interact with three-dimensional objects to perceive their spatial relations [58]). Nonetheless, future research on spatial ability moderators should take into account this potential interdependence between AR interventions and spatial ability measurements.

In addition to cognitive prerequisites, future research should also focus on affective learner characteristics, which have been found to be closely linked not only to AR environments [14,82] but also cognitive load and learning outcomes [83].

4.5. Practical Implications and Conclusions

This study is among the first to investigate how cognitive learner prerequisites impact the effectiveness of AR support in lab work learning environments. By re-analyzing the data from three studies involving different target groups and AR devices, it extends and refines the findings of the original research and helps to reconcile the ambiguous results. The findings suggest that AR can effectively support learners with low spatial abilities by relieving their working memory load. Moreover, learners with low verbal working memory appear to be particularly affected by the spatial contiguity failure that can be caused by smartglasses AR. However, AR smartglasses offer several advantages, especially for hands-free experimentation and a more immersive experience. As technology develops, their current limitations, such as the severely limited field of view, are likely to be addressed. These improvements could allow smartglasses to realize their full potential and increase their effectiveness in learning environments. From a practical perspective, the design and implementation of AR-supported learning environments should carefully consider the interplay of learning objectives, individual cognitive strengths and weaknesses of the target learners, and contextual factors such as accessible AR devices to create the most effective learning experiences.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Faculty of Empirical Human Sciences and Economics at Saarland University on 13 October 2021 for studies involving humans.

Informed Consent Statement: Informed consent was obtained from all the subjects involved in this study.

Data Availability Statement: This article involves the re-analysis of data from three previously described studies; no new data were generated. Details of the original studies are provided in [1,17,18]. For further information or access to the data used in this re-analysis, please contact the corresponding authors. Data will be made available upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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