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Media comparison studies dominate comparative research on augmented reality in education☆

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A R T I C L E I N F O

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A B S T R A C T

Research on the use of augmented reality (AR) in education has received a lot of attention in recent years. Based on many systematic reviews and meta-analyses, it has been concluded that AR is effective. Recently, however, researchers have criticized the fact that the empirical basis for this conclusion is based on results from methodologically problematic media comparison studies. However, an analysis of the literature and quantitative evidence for this claim are lacking. In this research project, this research gap was addressed using the Systematic Review method. A total of 92 primary studies from the top 12 *Educational Technology* journals were coded and analyzed. The results show that research on AR in education is based on media comparison studies: 80% of the studies compare AR to another medium or technology. Few studies examine how and when learning with AR is effective. In addition, results show that over the years, since 2009, more media comparison studies have been published than other research types. We summarize why media comparison studies are problematic and discuss directions for future research on AR in education. This research shifts from the question *if* AR can be used in instruction to the more important questions of *how* and *when* learning and teaching with AR works.

1. Introduction

Augmented reality (AR) is a contemporary visualization technology that extends sensory perception through digital objects. The key characteristics of AR have been defined by Azuma et al. (2001) as follows: real and virtual objects are displayed simultaneously, interactions run in real time, and both virtual and real objects are registered geometrically. Due to technological requirements, like the need for AR glasses, the use of AR has been limited to research institutes and the military sector during the 1990s and the early 2000s (Azuma, 1997; Billinghurst et al., 2015). With the advent of smartphone and tablet computers around 2007, this changes substantially because AR technology became available for everyday users (overview in Billinghurst et al., 2015). At the latest since 2016 with the release of the AR game Pokémon Go, AR technology has become familiar to the wider society and people understood that AR can be used just with a mobile phone (Qiao et al., 2019). Research on the use of AR as a possible technology for teaching and learning started with university projects on AR books (Billinghurst et al., 2001), followed by mobile AR applications and AR games using self-developed handheld computers (Klopfer & Squire, 2008; Squire & Klopfer, 2007). As of today, AR enhanced learning has extensively been explored and tested resulting in a large body of empirical studies considering different learner types, educational disciplines, and

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pedagogical approaches (Akçayır & Akçayır, 2017; Arici et al., 2019; Garzón et al., 2020). Based on AR, educators can design innovative learning environments that visualize the invisible, provide interactive and immersive experiences, and engage learners in gamified and motivating instructional scenarios (e.g. Bacca et al., 2019; Buchner et al., 2021; Buchner & Zumbach, 2020; Georgiou & Kyza, 2021; Krüger et al., 2019; Paraschivoiu et al., 2021).

The positive effects of AR in learning environments have been demonstrated repeatedly in empirical studies, which have been aggregated in systematic reviews and meta-analyses. In a meta-review, Radu (2014) reports that AR has positive effects on cognitive learning outcomes compared to other media, and after reviewing 68 published articles, Akçayır and Akçayır (2017) conclude that AR can promote learning motivation, understanding, satisfaction, and attitudes. Results of several meta-analyses show that the implementation of AR in education has a medium effect size between $d = 0.52$ and $d = 0.68$ regarding cognitive learning outcomes and knowledge acquisition (Garzón & Acevedo, 2019; Garzón et al., 2019, 2020; Ozdemir et al., 2018; Santos et al., 2014; Tekedere & Göker, 2016).

However, more recently, several researchers have expressed doubts about these findings because of methodological issues in the primary studies included in the systematic reviews and meta-analyses. For example, Zumbach et al. (2022) state that the empirical base for the effectiveness of AR in educational settings is grounded on inadequate media comparison studies. Similar, Garzón et al. (2020) criticize that studies predominantly try to prove that the application of AR technology can support learning while not considering the educational context.

More general, Honebein and Reigeluth (2021a, 2021b) express this concern for research on educational technologies. In a review of articles published in the *Educational Technology Research and Development (ETR&D)* journal, they examined that since 2010 the trend to conduct studies comparing novel technologies and/or instructional approaches to so-called "traditional instruction" increased. Honebein and Reigeluth (2021a, 2021b) further state that the increasing publication of these *comparative confounded* empirical studies is also observable for educational technology journals other than ETR&D. However, they do not provide evidence for this statement. The same is true for the statements in Zumbach et al. (2022) and Buchner (2022): the authors claim that empirical studies on AR in education are based on media comparisons, but evidence for this claim is lacking.

Although many systematic reviews and other types of literature reviews about research on AR in education are published (e.g. Arici et al., 2019), no review addresses what the authors of the primary studies compared (for exceptions see Buchner, Buntins, & Kerres, 2021, 2022). The methodological aspects that are reported in previous systematic and literature reviews concern if the empirical investigation was a true experiment, a quasi-experiment, a case study or another research approach; and if data collection was done using quantitative or qualitative instruments, or using the mixed methods approach (e.g. Ali et al., 2019; Arici et al., 2019; Ibáñez & Delgado-Kloos, 2018; Maas & Hughes, 2020; Pellas et al., 2019, 2020).

Therefore, in this research project, we aim to fill this gap in the literature by examining what researchers compare in empirical studies on AR in education. According to Reeves and Lin (2020; also Honebein & Reigeluth, 2021), the relevance of this question is high for at least two reasons: First, all findings reported in systematic reviews and meta-analyses are based on what have been done by researchers in the primary studies (Reeves & Lin, 2020). Hence, if the methodological quality of the primary studies is low, the conclusions in these reviews must be treated with caution. Second, comparison studies that use an instructional method or media as independent variable do not replicate in other situations (Honebein & Reigeluth, 2021). Hence, these studies can not help to improve educational practice.

The research questions that guided this study were as follows:

Research Question 1: Which types of comparisons do researchers use in empirical investigations on AR in education?

In the literature, several types of comparison approaches are described. As mentioned above, one approach compares a new technology, in our case AR, with a more traditional and established media or technology (e.g. video). Like the media comparison approach, the instructional method comparison approach compares a more-or-less novel instructional approach, mostly together with a new technology, with the so-called "traditional instruction" (based on textbook, paper-based instructional material, lecture, and so on; Honebein & Reigeluth, 2021). While these approaches are characterized as technology-centred or thing-oriented (Mayer, 2020; Reeves & Reeves, 2015b), two other approaches reported in the literature are called learner-centred (Mayer, 2014, 2020). The first learner-centred approach is known as value-added research. Empirical investigations following the value-added research approach compare the same instructional technology/technology-enhanced learning environment, but manipulate an attribute within it or add an instructional feature. For example, Schrader et al. (2018) investigated if learning with a multimedia presentation is better when a conversational or a formal language is used; Parong and Mayer (2018) examined if adding the learning strategy of summarizing to an immersive virtual reality (IVR) simulation enhances learning compared to learning with the same IVR simulation without the summarizing strategy applied. Mayer (2014) complements that also a value-subtracted research design is possible. Finally, in the aptitude-treatment-interaction (ATI) approach, also learner-treatment-interaction (LTI) approach, the characteristics of the learners are considered as factors influencing learning processes (Connor et al., 2014; Surry & Ensminger, 2001). For example, Zumbach et al. (2020) investigated if knowledge about metacognitive strategies supports learning with a simulation game.

Research Question 2: Is there a relation between year of publication and chosen types of comparisons?

The rationale for research question 2 is that even known critics of technology-centred comparison approaches, like Mayer (e.g. Parong & Mayer, 2018), see a necessity to compare a newly developed technology to a more traditional one. However, this phase of research is limited to give answers to the question *if* learning with a certain technology works. More essential for instructional theory and practice are questions examining *when and how* learning works (Mayer, 2020, p. 57). Specifically for research on AR in education, this has also been noted in Garzón et al. (2020) as well as in Mystakidis et al. (2022). Hence, it can be assumed that on the emergence of AR, researchers used technology-centred approaches investigating if learning with AR works; later on, empirical investigations apply more learner-centred approaches to contribute to the more relevant questions of when and how AR-enriched learning works.

2. Method

To answer our research questions, we applied the systematic review method. A systematic review is a systematically performed literature review with the aim to answer research questions. The method is characterized by a comprehensible search strategy guided by inclusion and exclusion criteria. The included studies are coded, synthesized, and used to answer the research questions (Newman & Gough, 2020).

2.1. Search procedures

To ensure high quality of the studies that will be scanned in our analysis, we decided to apply the hand searching strategy. This strategy includes the examination of specialist journals for a specified period of time (Alexander, 2020; Newman & Gough, 2020). In our case, we focused on the top 12 journals within the field of educational technology research according to the *Google Scholar Ranking: Educational Technology* and the *Scimago Journal Ranking: E-Learning*. The searched journals with their rank from May 10, 2020, are presented in Table 1.

Regarding the time span, we limited the search to articles published until 2020.

All homepages of the respective journals were searched several times for articles investigating learning and teaching with AR. We used the following search terms: "augmented reality", "AR", "mixed reality", "augmented learning", "augmented education", and "augmenting reality". A total of 167 publications were identified through this search which afterwards were screened considering the inclusion and exclusion criteria.

2.2. Inclusion and exclusion criteria

As we were interested in the types of comparisons researchers use to explore the value of AR in education, only primary studies with a comparative research design were included. For example, in such a design an experimental group is compared to a control group. Consequently, single-group studies were excluded. Also secondary research, like systematic reviews, meta-analyses, or other literature reviews, were not included in the final sample. Furthermore, studies without an intervention or an evaluation of learning outcomes were excluded. As the searched journals only publish articles in the English language, it was not necessary to define criteria about language.

2.2.1. Final pool

Through the hand search of the top 12 educational technology journals and the inclusion/exclusion criteria presented above, we included 92 studies (see Appendix 1) for the final analysis to answer our research questions. The screening process is given in Fig. 1. At the beginning, we excluded four editorials. Next, we screened the abstracts of the remaining 163 articles. Based on the abstract screening we were able to exclude 18 reviews. Afterwards, we read 145 full texts and further checked if the articles fit our inclusion criteria. Another 53 studies were excluded, because no comparative research design was used, or no learning outcomes were measured. Hence, our final pool of studies used for the in-depth analysis includes 92 studies.

3. Coding scheme

To answer our research questions, we coded all included studies based on the types of comparisons applied (RQ1) and the year of publication (RQ2).

The coding of the studies regarding the types of comparisons used was guided by the types outlined in the introduction. Empirical investigations that compared AR to other media or technologies were coded as media comparison study. Additionally, we searched for studies that compared "traditional instruction" to "AR learning" (or similar). However, during the coding process it has become evident that these studies also always compare AR technology other media or technologies. Therefore, we coded these studies as media

Table 1
Journals included in the search procedure with abbreviation, rank, and h-index.

Journal	Abbreviation	Rank	*h*-Index*
Computers & Education	C&E	1	149
British Journal of Educational Technology	BJET	2	81
Journal of Computer Assisted Learning	JCAL	3	80
Educational Technology Research & Development	ETR&D	4	79
Internet and Higher Education	IHE	5	75
Educational Technology & Society	ET&S	6	73
Journal of Research on Technology in Education	JRTE	7	49
Australasian Journal of Educational Technology	AJET	8	40
International Journal of AI in Education	IJAIED	8	40
IEEE Transactions on Learning Technologies	TLT	9	39
Interactive Learning Environments	ILE	10	34
Education & Information Technologies	E&IT	11	31

Note: *Data from May 10, 2020.

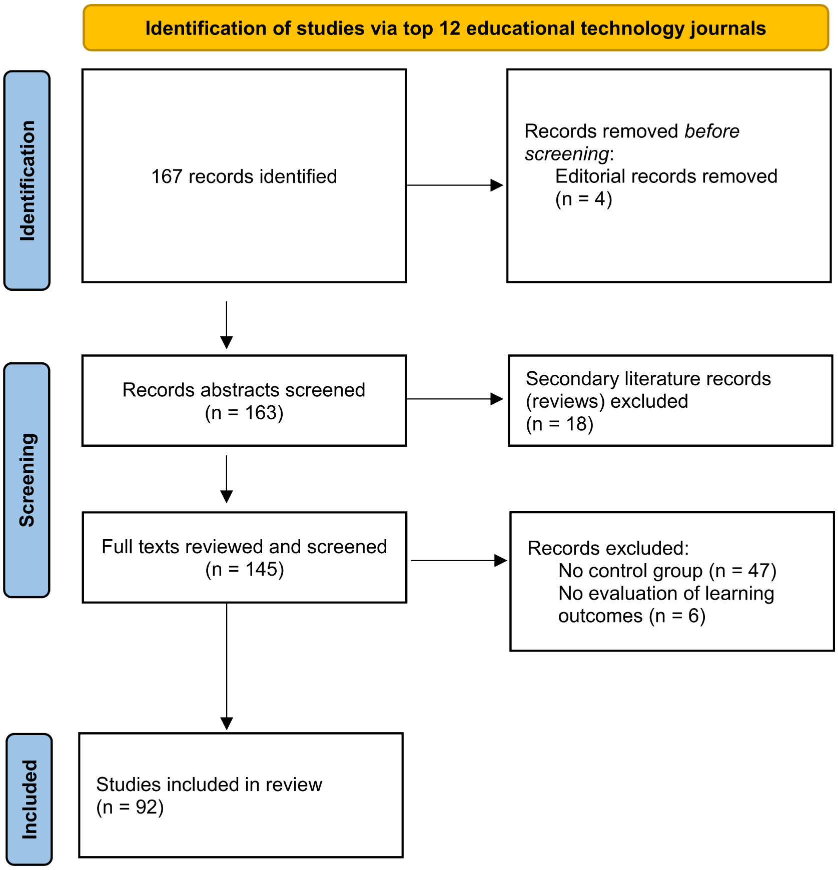

Fig. 1. PRISMA flow chart of the screening process based on Page et al. (2021).

comparison studies too. This is in line with Honebein and Reigeluth (2021, p. 475) who also found that comparisons with "traditional instruction" are *media-oriented*. The full list with all included studies and the wording used by the authors is available as Appendix 2.

Studies that compared two different versions of AR systems or AR learning environments were coded as value-added studies. Value-added studies contribute to the question how to design learning with a certain media or technology (Mayer, 2014, 2020). For example, in the experimental condition students use an AR application in combination with the learning strategy of summarizing while the students in the control condition use the same AR application but do not perform the summarizing activity.

Empirical investigations that compare the effects of an AR learning environment or application under consideration of learners'

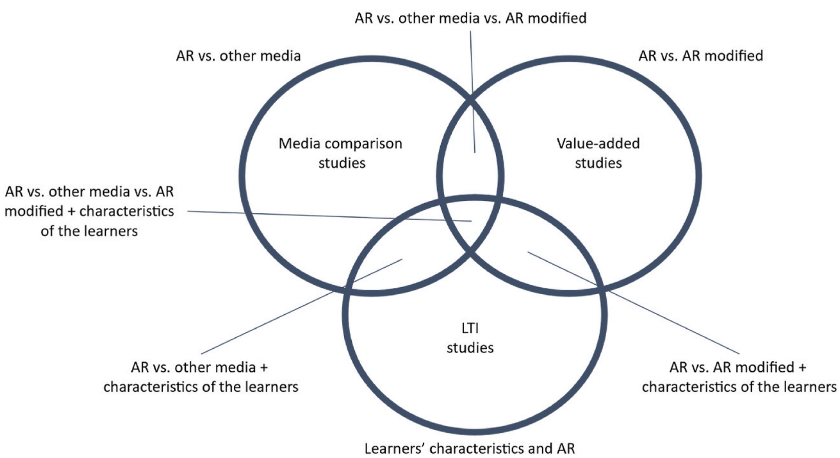

Fig. 2. Graphical summary of the types of comparisons coded in this research project.

characteristics were coded as learner-treatment-interaction (LTI) studies. As mentioned above, such studies are also known as aptitude-treatment-interaction (ATI) studies (Connor et al., 2014; Surry & Ensminger, 2001). Results of LTI studies help to understand when learning with a certain media or technology works.

Furthermore, during the coding process, we identified studies that applied more than one comparison approach. For example, studies compared AR to video by considering the gender of the participants (media comparison study + LTI study); and studies compared an AR learning environment to a slightly modified AR learning environment to paper-based instructional materials (media comparison study + value-added study). Hence, we coded these studies as combinations of types of comparisons accordingly. Fig. 2 illustrates a summary of the codes used according to the comparative designs applied by researchers in our pool of studies.

Year of publication was examined from the published articles and coded as a number; for example, 2019.

4. Results

First, we present some basic information about our final pool of studies followed by a detailed presentation of the results for each research question.

In Table 2 the distribution of the 92 studies among the top 12 educational technology journals is given. Most of the studies are published in *Interactive Learning Environment* (ILE; $n = 25$) and *Computers & Education* (C&E; $n = 24$). Studies published in these journals account for more than half of the studies analyzed in this research project. Considerably fewer studies were published, for example, in the *British Journal of Educational Technology* (BJET; $n = 7$), in *Educational Technology & Society* (ET&S; $n = 8$), and the *Journal of Computer Assisted Learning* (JCAL; $n = 7$).

Further, the data shows that research on AR in education is still increasing. In 2019 and 2020 almost twice as many studies were published compared to the years 2017 and 2018 (Fig. 3).

Research Question 1: Which types of comparisons do researchers use in empirical investigations on AR in education?

The first goal of this research project was to examine which types of comparisons researchers use when they conduct empirical investigations about the value of AR in education. In 74 studies (80.4%) researchers compared AR to other media or technologies. In 20 studies (21.7%), a value-added approach was chosen to investigate teaching and learning with AR. In further 10 studies (10.9%), characteristics of the learners were considered, representing LTI studies. In 81 studies (88.0%) one type of comparison was applied, in 10 studies (10.9%) two types, and in one study (1.1%) all three types of comparisons were used. An overview of the distribution of the studies according to the comparison types is presented in Fig. 4. In 63 studies (68.5%), of the 81 studies applying one comparison approach, researchers compared AR to other media or technologies. In 13 studies (14.1%) the value-added approach was used, and five studies (5.4%) were identified as LTI studies. Further, six studies (6.5%) used the media comparison approach and the value-added approach; four studies (4.3%) combined media comparison with LTI; and one study (1.1%) used all three types of comparisons. No study investigated the effect of two different AR learning environments while considering the characteristics of the learners (Value-added study + LTI study).

Research Question 2: Is there a relation between year of publication and chosen types of comparisons?

The second goal of this research project was to examine if the types of comparisons applied in primary studies on AR in education changed over time. Firstly, Fig. 5 shows that media comparison studies not only dominate, but also increase each year. The peak in media comparison studies to date is 2020, with 17 such studies. Further, the data shows that starting in 2016 more value-added studies were conducted. LTI studies occur irregularly until 2019; the influence of learner characteristics seems to have only recently attracted AR researchers' attention.

Secondly, Fig. 6 shows that the pure media comparison approach is by far the most used comparison type in studies on AR in education. This is also true for more recently published studies. For example, in 2019 13 studies compare AR to other media or technologies, twelve in 2020. Only in 2012 no pure media comparison study was published. However, both studies published in 2012 combined either a value-added research design or a LTI approach with the media comparison approach. Regarding the combined use of different comparison approaches, the data shows an increase of combined studies. For example, in 2020 each single type of comparison and each combination found in the pool of studies was used.

Table 2
Distribution of studies among the 12 journals.

Journal	*f*	%
C&E	24	26.1
BJET	7	7.6
JCAL	7	7.6
ETR&D	3	3.3
IHE	1	1.1
ET&S	8	8.7
JRTE	1	1.1
AJET	2	2.2
IJAIED	2	2.2
TLT	6	6.5
ILE	25	27.2
E&IT	6	6.5

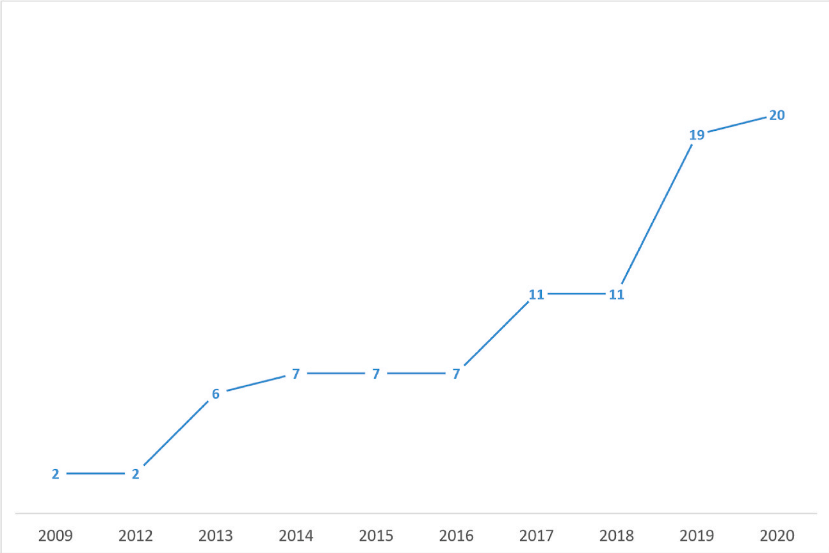

Fig. 3. Distribution of studies per year of publication.

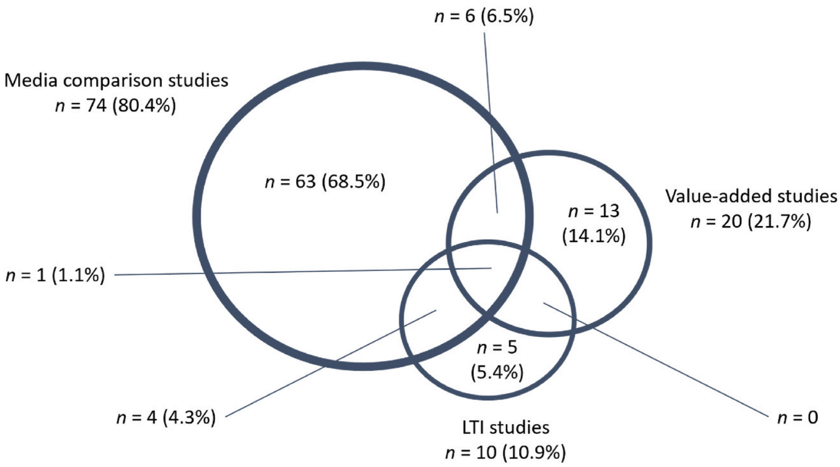

Fig. 4. Graphical summary of the types of comparisons used in studies on AR in education.

5. Discussion

The aim of this research project was to present an in-depth analysis of designs of empirical investigations about the effects of AR in education. The need for such a critical analysis of the AR literature is high, as several scholars have expressed doubts about the methodological quality of published studies. Furthermore, this study addresses the more general call for critical investigations about the research practices used in the field of educational technology research (e.g. Teräs et al., 2020; West et al., 2020; Wright, 2018). Hence, we conducted a systematic review of primary studies using comparative research types and published in the top 12 educational technology journals. The research project was guided by two questions, which are now discussed in detail based on the results discovered.

RQ1: Which types of comparisons do researchers use in empirical investigations on AR in education?

With respect to research question one, the data found shows a clear picture about the nature of comparative AR research published so far: Most studies (80%; $n = 74$) about AR in education follow a media comparison approach. Value-added studies and LTI studies are subordinate in importance. Moreover, each study using a combination of comparative research approaches still compares AR with other media or technologies. Another meaningful finding is that no study in this review has combined the value-added approach and the LTI approach without media comparison. However, studies using these two approaches might provide remarkable insights beyond the question if learning with AR is possible. For example, such a study can help to understand when an AR learning environment with a specific learning activity is more beneficial, for example, for younger or older students, or learners with high/low prior knowledge in a

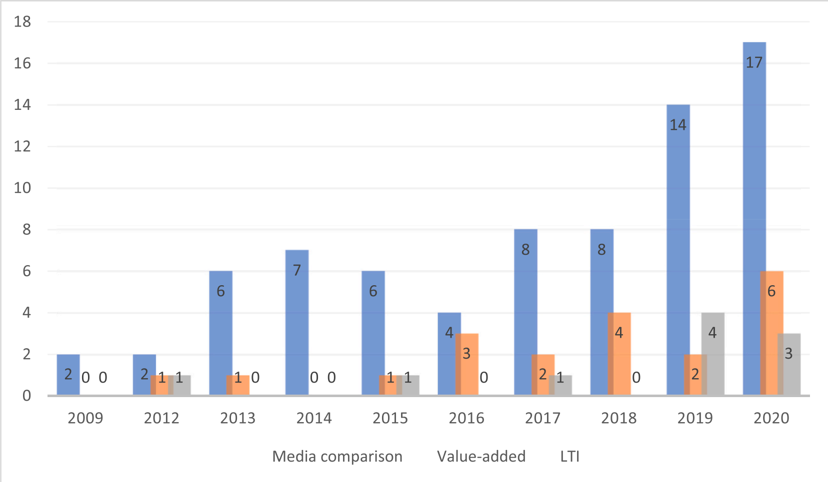

Fig. 5. Distribution of the three main types of comparisons per year of publication.

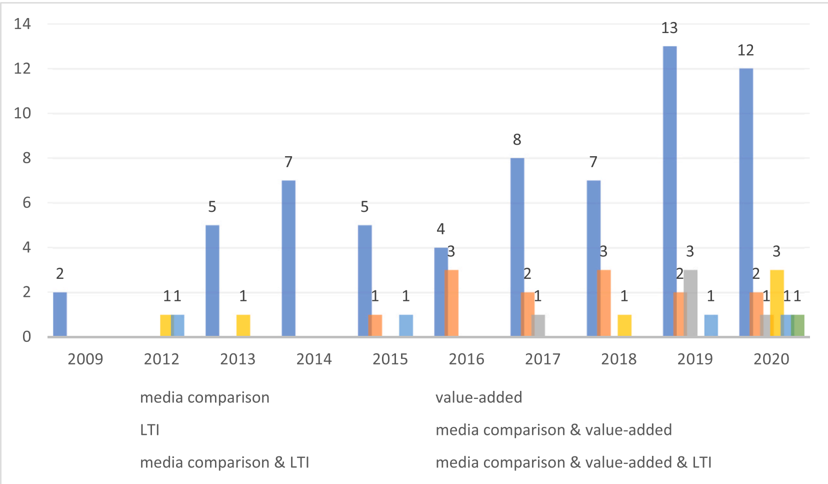

Fig. 6. Distribution of the main types and combinations per year of publication.

learning domain.

As mentioned in the introduction, media comparison studies are under criticism for more than forty years; but why are media comparisons problematic?

First, media comparison studies are based on a technology-centred understanding of teaching and learning. This understanding assumes that media and technologies influence learning, but neglects the complexity of instruction (Clark, 1983, 1994; Honebein & Reigeluth, 2021a; 2021b; Kozma, 2000; Ross et al., 2010).

Most popular in this discussion is the *great media debate* (Sickel, 2019) between Clark (1983, 1994) and Kozma (1991, 1994): Clark argued that media are more vehicles delivering instruction, while Kozma argued that specific media has unique attributes affecting learning. Both positions have been intensively discussed by scholars (e.g. Koumi, 1994; Ross, 1994), also leading to misinterpretations. For example, Clark never claimed that the decision for a learning technology is irrelevant, and Kozma never claimed that learning with media is better than without. In fact, both Clark and Kozma agreed that learning and instruction is complex and needs, for instance, alignment of media and method considering the learning objectives (Hastings & Tracey, 2005; Surry & Ensminger, 2001).

However, researchers continued comparing newly developed technologies to traditional media hoping for an educational revolution because now this technology will change learning fundamentally (Bozkurt, 2020; Mishra et al., 2009). In fact, every media and technology can be used to deliver effective and engaging instruction, if well-designed, using the full repertoire of instructional methods. The reason for effective learning is never solely due to the technology used (Feldon et al., 2021; Honebein & Reigeluth, 2021b; Mayer, 2020). Consequently, *comparing the learning benefits of different media are a waste of resources* (Clark & Feldon, 2014, p. 153).

Second, from a methodological perspective, media comparison studies are *inherently flawed* (Hastings & Tracey, 2005, p. 30). This means that in media comparison studies researchers can never guarantee for the same conditions in the experimental and the control group. Surry and Ensminger (2001) refer to Reeves (1995) who has summarized characteristics of poorly designed media comparisons. Among others these include the lack of linkage to robust theories of learning and instruction as well as a focus on results of other studies in the literature review that support the idea of better learning with the technology under investigation. Ross (1994) complement that even randomized media comparison studies using the same instructional method in the experimental and the control group are not a good way to investigate the value of educational technologies. In such studies, the outcome is clear aforehand contributing to an increase of studies reporting no significant differences (see DETA Research Center, 2019; Reeves & Oh, 2017).

Third, media comparison studies neither inform theory nor practice. As mentioned above, most media comparison studies do not refer to theories of learning and instruction (e.g. Hew et al., 2019), hence, no development of such theories is possible. The results of media comparison studies also do not help educational practice. The first problem is that media comparison studies are single-shot studies that do not replicate in other situations. This is because some learning environments work in one situation, but not in the other. Every learning environment is situational (Honebein & Reigeluth, 2021b); hence, practitioners can never establish the same situation in a classroom. Second, in practice, instruction is a process that do not ends with one lesson using AR or another technology. A good teacher will always use a great variety of media and methods to support the learners in aiming their learning objectives, while considering contextual factors like prior knowledge. Third, media comparison studies investigate if learning with AR works compared to other media. As mentioned above, teachers can use every media and technology to design effective and engaging, or inadequate learning environments. Hence, it is not helpful to know if AR is better than learning with a textbook because it is easy to show that learning with a textbook is equal effective, or more effective, than learning with AR by just using more effective learning strategies in the textbook control condition (for an example see Zumbach et al., 2022). For a teacher, it is a daily concern to design learning environments that help learners learn. Hence, teachers do not need the information if learning with AR is better or equal effective like learning with the textbook, but they need information about when and how learning with AR works. To provide information about when and how learning with AR works, value-added and LTI research designs are required (for an example see Krüger & Bodemer, 2022).

RQ2: Is there a relation between year of publication and chosen types of comparisons?

We expected that early empirical investigations on AR in education applied the media comparison approach, while later more research studies would use other types of comparisons. As the results show, this expectation was not confirmed. Media comparison studies dominate research on AR in education since 2009; in fact, an increase in such studies is evident in 2019 and 2020. Another result is that more studies combine the types of comparisons since around 2016. The question is, why do researchers still use the media comparison approach? First, comparing a new technology with an older one is easy to implement (Surry & Ensminger, 2001). For a media comparison study, two groups are needed: One group learns with the new technology, the other with the old technology. To analyze possible differences between the two groups, simple statistical methods can be used (Wright, 2019). Second, media comparison studies are crisis-proof because newer technologies will always be invented. For example, if a technology company introduces a supposed new technology, like a *Metaverse,* the next innovative study is easily designed: One group of learners uses the *Metaverse* and the control group AR. This kind of research is thing-oriented research, i.e., it is more important to publish an article about a "trendy technology" than planning and conducting a sound empirical investigation that examines solution for educational problems (Reeves & Reeves, 2015a; 2015b). To summarize the results for RQ2, we conclude that most research on AR in education was, and currently is, concerned with the question if AR works. Hence, it is important to move forward, leaving the if-phase behind and starting to provide information about when and how learning with AR works.

6. Implications

The results of this study demonstrate that reconsidering research about AR in education is needed. Therefore, we provide recommendations for researchers how to conduct future research on this topic. Further, the results are important for journal editors and reviewers as these persons are responsible for future studies to be published or not. Also, the findings affect educational practice. Details are presented in the following sections.

6.1. Future research

Many media comparison studies investigated if learning and teaching with AR works. In conclusion, these studies demonstrated that a well-designed AR learning environment or AR application can support learning. Consequently, researchers can move forward and investigate more relevant questions regarding *when* and *how* learning with AR works. With respect to *when,* we distinguish between learner characteristics and learning outcomes. To investigate the impact of learner characteristics when learning with AR, we introduced the LTI research approach. Such an approach is, for example, used in Adedokun-Shittu et al. (2020). In this study, the authors investigated if learning about geography with an AR tool is effective for both female and male students. In Conley et al. (2020), prior knowledge was used to examine the effectiveness of an AR game. Further learner characteristics that might influence learning with AR are, for instance: self-efficacy, age, curiosity, and experience with AR technology. The latter is of high interest to control for the novelty effect. For example, it is possible that more AR experienced learners are less fascinated when using AR affecting their engagement. Zumbach et al. (2022) report that knowing of and readiness to apply learning strategies impacts learning with AR. Hence, it would be interesting to investigate benefits of higher awareness of learning strategies when learning with AR. *When* also addresses learning outcomes, i.e., different AR learning environments or AR applications might affect learning outcomes differently. For example, Habig (2019) used AR in chemistry education to test if students are better able to solve two-dimensional or three-dimensional tasks. In another example, Deshpande and Kim (2018) examined if learning with AR is more effective for simple or complex procedural learning tasks.

The question *how* learning with AR works can be investigated applying the value-added research approach. For example, Wu et al. (2018) compared an AR application about butterflies with a modified version of the AR application. In the modified version, the learners saw a repertory grid on the screen in which students summarized the information about the butterflies observed. The students in the modified group outperformed the group not using the repertory grid. This study shows that combining advantages of AR, here visualization of science content, with learning strategies is effective. Another example is the study presented in Oh et al. (2018), in which the authors examined the effects of a game-based and a non-game-based AR simulation presented to the learners in different orders. Many other modifications are possible to investigate, how learning with AR works better. Further examples, for instance, are comparisons modifying the principles of Mayer's Cognitive Theory of Multimedia Learning (e.g. Mayer, 2020) like in Krüger and Bodemer (2022), testing if generative learning strategies also work in combination with AR (Buchner, 2022; Fiorella & Mayer, 2021), varying the situational context (Georgiou & Kyza, 2021), or researching if gestures and whole body movements affect learning with AR-enriched simulations (Lindgren et al., 2016).

Table 3 provides an overview for future research addressing when and how learning with AR works.

Additionally, we provide an example combining LTI with the value-added approach. In this review, no study applied this kind of combination. However, this combination can contribute to a better understanding of when (e.g. considering prior knowledge) and how (e.g. with or without an added learning strategy) learning with AR works.

To conclude, we would like to recommend researchers to avoid conducting media comparison studies in the future and to start using LTI, value-added, and combined research designs to contribute to a better understanding of *when* and *how* AR supports learning and teaching.

6.2. Journal editors and reviewers

Researchers criticize the media comparison approach for more than 40 years (e.g. Clark, 1983, 1994; Hastings & Tracey, 2005; Hodges, Moore, et al., 2020; Ross et al., 2010; Surry & Ensminger, 2001). However, as the data in this study shows, research on AR in education is dominated by this type of comparison. Editors and reviewers can assist in ensuring that such studies are published less frequently. For the following recommendations, we have been guided by Honebein and Reigeluth (2021b, pp. 483–485), who compiled a comprehensive overview.

Editors should revise the *Instructions for Authors* and supplement a section that summarizes the problematic of the media comparison approach. Further, editors should provide information for the reviewers about the journals policy regarding media comparison studies. If an editor nevertheless decides to submit a (possible) media comparison study for review, reviewers who are familiar with the issue should be involved.

Reviewers should critically examine the assigned paper and check if the authors conducted a media comparison study. If yes, further analyze the *Theoretical Background/Framework* to understand why comparing AR with video or paper-based instruction should be of interest. If the background information relies heavily on other AR studies, the theory part is insufficient (Reeves, 1995). Furthermore, reviewers should carefully read the introduction to understand the problem to be solved by this study. If the problem is thing-oriented (Reeves & Reeves, 2015b), like is AR better than a textbook, the results of the study do not help educational theory or practice; hence, reviewers should reject the manuscript including a decision letter explaining to the authors why the research design applied is insufficient. As usual with quality reviews, use objective language, references, and do not embarrass the authors. The review should increase authors understanding why media comparison studies are flawed; consequently, it helps authors conducting future research studies investigating when and how learning with AR works.

6.3. Educational practice

The implications for practice are twofold. First, the results of this study show that research on AR in education focused on the question if learning with AR works. The problem with this research is that practitioners cannot use the findings of the studies in classroom teaching because the instructional design used is situational and, therefore, is not replicable. Further, the studies do not consider the educational context, like prior knowledge or learning objectives; therefore, the results do not reflect the complexity of instruction (Honebein & Reigeluth, 2021b). More research is needed about when and how AR in education works to inform real-classroom teaching and learning. Results from such studies might help to establish a more general AR instructional design model like suggested in Mystakidis et al. (2022).

Second, educational practice also involves how PhD supervisors, professors, and research lab leaders guide early career researchers and students during planning and developing empirical investigations about AR in education. These persons should address the quantity of media comparison studies in the field of educational AR research and initiate discussion in their teams why such studies are problematic. As a result, we expect more studies investigating when and how learning with AR works. We recommend the presentation given by Hodges, Curry, and Grant (2020) as a starting point for discussions how to do research on educational technologies in general and AR in particular.

7. Limitations

The results of the study are limited due the methodological approach used. We focused in this systematic review on the top 12

Table 3
Overview of comparison types to investigate when and how learning with AR works.

Research goal	Comparison based on	Type of comparison	Example
When (Learner characteristics)	Gender, age, prior knowledge, previous experience, …	Learner-Treatment-Interaction design (LTI)	Compare a group of learners with less AR experience to a group of learners with high AR experience.
When (Learning outcomes)	Simple/complex tasks; declarative/procedural knowledge, …	Value-added design	Compare two different AR learning applications and their effect on solving a simple or complex problem.
How	Individual/collaborative; learning activity A/B, …	Value-added design	Compare if learning with an AR book is better when students engage in a summarizing or a drawing activity.
When & how	Previous AR experience + learning strategy; prior knowledge + simple/complex task, …	Combination of LTI & value-added design	Compare, if students with low/high previous AR experience benefit more when using a summarizing activity or not in an AR-enriched lesson.

educational technology journals (as of May 10, 2020). The ranking has changed in the meantime; hence, an extension of included journals is necessary. Further, other journals reported in the literature (e.g. Arici et al., 2019) publishing many AR studies should be included, for example, *Computers in Human Behavior.* We are already working on these limitations by analyzing articles published in *Research and Practice in Technology Enhanced Learning, TechTrends,* and *International Journal of Educational Technology in Higher Education.* This research project is ongoing, updates will be presented on our project page (LINK BLINDED).

Furthermore, we only analyzed studies that applied a comparative research design. Studies that used a design- or development-oriented research approach without a control group were missing.

Another limitation is our main interest in studies on AR in education. However, as researchers actively contributing to the knowledge base about how and when AR works in education, this limitation is justified for us. Future systematic reviews can use the coding scheme introduced in this study to analyze the types of comparisons applied in studies examining other educational technologies. For instance, immersive virtual reality, computer games, escape room games, educational video, or virtual simulations.

8. Conclusion

Researchers have increasingly criticized that the empirical base on the effects of AR in education is based on the methodologically debatable type of media comparison research. In this study, this claim proved to be true as the results of our systematic review show. Most primary studies on AR in education, published in the top twelve educational technology journals, compare AR with other media or technologies (80%). Moreover, the data shows that media comparison studies have increased, not decreased, since 2009. Because of the limited seriousness of such study designs, like summarized above, we conclude that research on AR in education, to date, mainly investigated *if* learning and teaching with AR works. In fact, researchers, and practitioners, should acknowledge that AR can be used to design effective and engaging learning environments; but so can ineffective and poor learning environments be developed using AR. Establishing *when* and *how* learning and teaching with AR is beneficial must be the goal in future research. Consequently, study designs beyond the media comparison approach are necessary. For example, we recommend conducting studies applying value-added, learner-treatment-interaction (LTI), or combined study designs. The results of such research projects can inform both theory and practice and contribute to the more important questions of *when* and *how* learning and teaching with AR works.

Credit author statement

Josef Buchner: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Michael Kerres: Investigation, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that there is no conflict of interest.

Data availability

Data is available via the supplementary material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2022.104711.

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