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How handheld use is connected to learning-related factors and academic achievement: Meta-analysis and research synthesis

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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

Handhelds (e.g., cell phones, tablets) are promising learning tools, so they are now used in formal classroom settings in many educational institutions around the world. Previous meta-analyses have focused predominantly on the direct effects of handhelds on academic achievement. From a psychological perspective, however, achievement is the outcome of a complex and multifaceted process involving adaptive cognitions and motivation for learning. While these factors are also themselves desirable learning outcomes, previous meta-analyses have neglected the effect of handheld use on these outcomes. This meta-analysis is the first to synthesize how the use of handhelds in formal educational contexts is associated with a broad range of motivational (e.g., intrinsic motivation, self-efficacy) and other learning-related factors (cognitive load, satisfaction with learning, attitude towards learning) beyond academic achievement. The question *how* handhelds can be used most effectively in learning settings is also addressed by considering studies' learning designs. We included 59 samples ($N = 4259$) in 58 studies published between 1998 and 2021. Only studies with an experimental or quasi-experimental research design providing pre- and/or post-test data and comparisons between experimental and if available control groups were included. We found overall moderate to high effect sizes for learning-related factors (*g*s between .41 and .77) and for academic achievement ($g = .71$). None of the presumed moderating variables (handheld types, learning designs, students' age, gender) significantly explained heterogeneity in the respective outcomes. Our findings demonstrate a broad range of positive effects of handheld use thereby implying a multicriterial, sustainable impact on educational trajectories.

1. Introduction

Cell phones, tablets, and other handhelds[1] have become an integral part of everyday life and are also increasingly used for digitally-supported-learning in educational institutions [28]. Today, the majority of young people between 12 and 19 years use cell phones and tablets for both leisure and studying activities [1,26]. The rapid technological development, distribution, wide range of functions, and the general benefits of handhelds have created new avenues for learning and achievement [8,29,82]. Many countries around the world promote state-funded initiatives for the use of handhelds, especially tablets, in primary and secondary education to support digital advancements and successful learning [72]. In line with the proliferation of handhelds across schools and universities, several narrative literature reviews, systematic reviews, and meta-analyses have explored the effects of (mobile) devices in different age groups of learners in various learning contexts mostly on academic achievement (e.g., [7,15,17,19,25,36,40,68,71,84,85]).

These previous studies have revealed a significant positive association of handhelds and other devices with academic achievement (Fig. 1, path a). From a psychological perspective, achievement is the outcome of a complex process in which learners actively interact with their environment in acquiring knowledge and skills [9,20,57,58,59,86]. Several psychological variables and environmental features can consequently impede and facilitate this process and thus make achievement more or less likely (e.g., [32,62]). In a similar vein, activity theory [5] places activity, a complex interaction between learners with digital devices such as handhelds on one hand and their environment as one

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[1] In this study, the term handhelds as a subgroup of mobile devices encompasses various technical mobile devices that can be carried in one hand. Our understanding of the term "handhelds" is corresponding to the definition used for mobile handheld devices by Cheung & Hew [16]. According to this study, mobile phones, cell phones, smartphones, tablets, personal digital assistants (PDA), personal mobile tools (PMT), pocket computers, phablets, and E-book readers are included.

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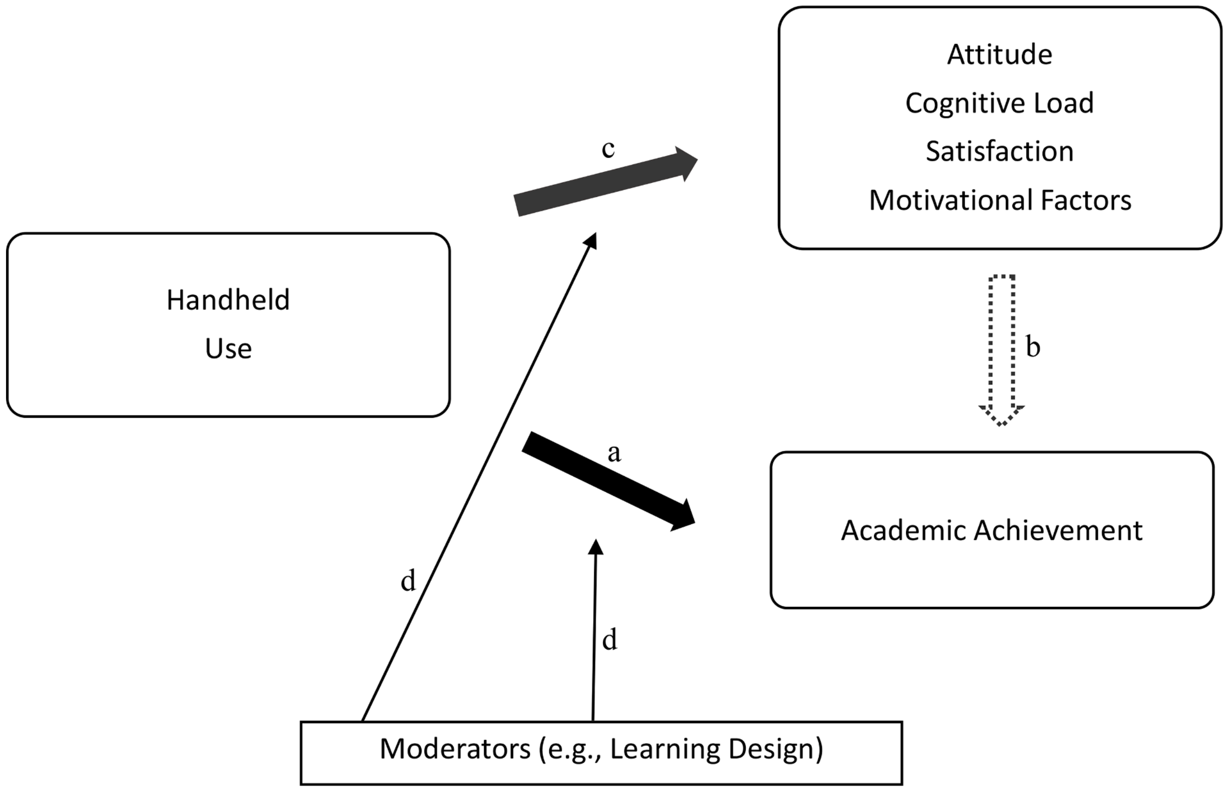

Fig. 1. Theoretical Framework for Effects of Handheld Use in Educational Settings.
Note. Dotted arrows indicate potential connections between different learning- and achievement- related outcomes in digital learning settings.

unit on the other hand, at the heart of analyses and suggests several components (e.g. subject, objects, context, rules) supporting or preventing effective (mobile learning) interactions. Both theoretical perspectives suggest that, for example, students' attitudes and individual evaluations about learning (e.g. attitude and satisfaction about learning), intrinsic motivational and other related variables (self--efficacy) play a major role in enhancing academic achievement and success. This has been shown in many prior studies and meta-analyses in analogous contexts. There is scientific consensus in educational psychological research that especially motivational factors such as intrinsic motivation and self-efficacy are important antecedents, mediators, or moderators of the learning process and academic achievement ([24,44,62,66]; c.f., Fig. 1, path b). For example, motivated students put more time and effort into studying, deal more adaptively with challenges and setbacks, and thus achieve better grades [4,30]. Therefore, most education systems and many organizations encourage education worldwide to empower students in their personal development, promote their interests, attitudes, and learning motivation and provide them with a general enjoyment for learning and skills for self-regulated, lifelong learning beyond knowledge transmission and enhancing academic achievement [53,75].

Although there are primary studies investigating effects of handheld use in formal educational settings for example on learning motivation (Fig. 1, path c; e.g.,) and satisfaction with learning (Fig. 1, path c; e.g.,), to date, there is no meta-analytic summary on these effects. A thorough recognition of how handheld use affects such outcomes is particularly important in order to understand whether and through which mechanisms learning-related factors enhance academic performance. Otherwise, if we treat learning-related factors in digital learning contexts as a black box, we risk overlooking both positive and potentially harmful consequences of handheld use (e.g., cognitive overload, attention problems, lower frustration tolerance) on learning-related factors. With this understanding, our ability to provide practical, evidence-based recommendations for the implementation of handhelds into formal educational processes will improve. Therefore, in the present meta-analysis, we initially examine whether the use of handhelds is associated with desirable learning-related factors, while including academic achievement as an additional outcome[2] (see Fig. 1, path a and c). In addition, we inspect a variety of potential factors (e.g., type of handhelds, educational level/ subjects, learning design) that might influence these relationships (see Fig. 1, paths d).

Notably, this meta-analysis goes beyond the usual consideration of the relationship between technology use (here handhelds) and performance outcomes by taking into account the learning designs (didactic concepts, methods and style realized by the teachers, e.g., frontal teaching, cooperative learning) in which the handhelds are used. This is important to guide teachers and other practitioners regarding *how* handhelds can be used most effectively in classrooms and university courses.

2. Previous meta-analyses on using mobile devices in educational contexts

Over the last five years, many reviews have been conducted focusing on diverse aspects of using mobile devices in varying degrees of granularity, in different settings, and with different methods and

[2] We decided to also include academic achievement as an outcome in the present meta-analysis for three reasons. First, we believe that the inclusion criteria applied here are more rigorous than in previous meta-analyses, so it would be interesting to see to what extent positive effects of mobile devices on academic achievement could be replicated. Furthermore, the diverse mobile devices, the associated software and in general the technical and didactic possibilities are developing fast which is why it seems appropriate to report an update on the influence on academic achievement if possible. Third, only a few meta-analyses have specifically reported the effects of handhelds as a special form of mobile devices.

perspectives. These reviews mostly try to structure, sort, and then summarize the complex mix of devices, technologies, methods, and learning designs (see [42]). However, it is difficult to directly compare these reviews and their results with each other because different devices (e.g., tablets, cell phones, laptops) are often analyzed under the general term "mobile devices". Additionally, most of these studies so far have concentrated on effects of whether or not mobile devices were used and less on effects of how mobile devices are used (i.e., the didactic concept, usually referred to as learning design).

Overall, while a great number of these studies are narrative or systematic reviews without inferential statistical analyses (e.g., [16,25,85]), only some work has included quantitative syntheses in forms of meta-analytical estimations of relations between constructs (e.g., between mobile devices and academic achievement). This is why we narrow the following review of previous research syntheses on quantitative meta-analyses in the field (see Table 1 for a complete summary and overview of previous meta-analyses on using mobile devices in educational contexts). Sung et al. [68] reported meta-analytical results of the effects of integrating various mobile devices in teaching and learning (during the period 1993–2013) and found a moderate mean effect size of $g = .52$ for the application of mobile devices on academic achievement in various learning contexts. The moderator analyses showed greater effects for handhelds compared to laptops, for inquiry-oriented learning compared to implementations in lectures, self-directed study, cooperative learning, and game-based learning, for use in informal educational environments compared to formal environments, as well as for medium- and short-duration interventions compared to long-term interventions ([68], p. 265). Moreover, a supplemental analysis of 22 studies revealed an overall moderate positive effect of mobile devices on a sum score of several learning related factors, summarized as "affective variables" ($g = .43$). Despite the findings of decades of educational research conceptualizing motivation and other learning-related factors as multidimensional and dynamic aspects [22,60,80], Sung and colleagues did not link the analyzed constructs to these theories and concepts (e.g., motivation, engagement, attitude, satisfaction, preference, participation) and did not present the results separately for each variable. Thus, it remains unclear to which extent integrating mobile devices in teaching and learning influences specific aspects of learners' motivation and affect. In addition, this reported effect size circumscribed all types of mobile devices and all types of instructional settings, including use in informal contexts. All in all, this approach severely limits the validity of this first meta-analytic sub-analysis of learning-relevant factors and requires a separate consideration of different factors relevant to learning given major conceptual differences between these variables.

Also, Chauhan [14] provided meta-analytical effects of the impact of technology on learning effectiveness of elementary students (based on published studies after 2000) and found a moderate mean effect size of $g = .55$ that technology leads to "effective" learning of elementary students. Her analyses indicated greater effects for general and science subjects, for longer interventions, and for technology use in informal learning settings. Learning-related factors besides academic achievement were not considered at all in the Chauhan meta-analysis. Cho et al. [17] reported meta-analytic results of the effects of using mobile devices on student achievement in language learning (during the period 2005–2017) and found a moderate mean effect size of $g = .51$ which overall parallels the findings from Sung et al. [68] and Chauhan [14]. Moderator analyses pointed to the importance of publication outlets and researcher-made scales for the assessment of language-learning achievement. Again, however, learning-related factors were not recognized as important outcomes in any case. Talan [71] conducted a meta-analysis based on studies from 2009 to 2019 and reported a high mean effect size of $g = .85$ of using mobile devices on students' academic achievement. Moderator analyses showed that the effect sizes differed depending on the subject. Based on studies published during 2008 to 2018, Chen et al. (2020) conducted another meta-analysis on the effects of using mobile devices on language learning, reporting an overall effect size of $g = .72$. More than 90% of the included studies referred to English learning as target language. Target language skill, target language (effects were remarkably lower for Chinese compared to English learning), and first/second language were found to be significant moderators. Overall, the effect sizes in Talan [71] and Chen et al. (2020) turned out to be higher than in the other meta-analyses by Sung et al. [68], Chauhan [14], and Cho et al. [17], while learning-related factors were not examined in the Talan meta-analysis.

In summary, academic achievement is a well-established and analyzed outcome of different forms of mobile device use in several learning settings. Different variables have been investigated that explain this relationship (moderator analyses), but these mainly relate to learning context (rarely on the way in which mobile devices are used, e.g., learning design). While a number of primary studies have examined effects of handheld use on several different and important learning-related factors besides achievement, such as self-efficacy (e.g.,), intrinsic motivation (e.g.,), autonomy (e.g., Katz, Y. J., 2015), or perceived relevance of learning material and subject (e.g., [52]), to date, there is no meta-analysis reflecting the multidimensionality of these variables. Furthermore, some previous meta-analyses showed methodological problems such as regarding the quality of included primary studies (e.g. unclear control groups, definitions and operationalizations of investigated variables) or not naming and specification of included types of mobile devices (see Table 1). Therefore, the present work provides meta-analytically inferred effect sizes of handheld use on various learning-related factors as well as academic achievement, taking into account different learning designs in formal educational settings.

3. Learning-related factors beyond academic achievement

3.1. How to investigate learning-related factors

Considering academic achievement as the sole outcome of handheld use in formal educational settings may lead to biased or incomplete conclusions in several ways. For one, we do not get the entire picture of effects of handheld use, but only a small cutout of it. Learning is not a direct function of teaching and being taught, but occurs in interaction between an individual and the environment. Therefore, to some degree it is always an individual and self-directed process [9,59,86]. We know from educational psychological theory and research, as well as from broad theoretical frameworks frequently used to examine effects of digital learning environments on performance, such as activity theory [5], that a large number of factors such as motivation, emotions, learning strategies, and the perception of several task and environment features guide this self-directed learning process [9,86] and represent important conditions for the sustained attainment of good achievement (e.g., [9,62]). Considering achievement alone therefore cuts short our understanding on how and why handheld use as an environmental feature affects learning and achievement.

Second, it is conceivable that the effects of handhelds will translate into higher achievement only after a longer period of time, but that significant effects on learning-related factors such as self-efficacy can already be demonstrated in the short term, which in turn may contribute to better achievement in the long run. Such a pattern would be plausible given empirical findings that prior school performance is the strongest predictor of subsequent school performance (even ahead of intelligence and motivation, [65]), thus seeming relatively stable (see also [45]), whereas in contrast, for example, motivational factors have been found to be malleable in the short term [12,41]. Studies only measuring achievement may thus reach biased and incomplete conclusions regarding the positive effects of handheld use depending on their study design.

Third, the consequences of using handhelds in formal educational settings are probably not universally good or bad as it has been reported for many instructional features. For example, gamification concepts may

Table 1
Previous meta-analyses on use of mobile devices in educational contexts since 2015.

Study	Focused Devices	Outcomes	Sample	Learning Settings	Number of Studies	Summary of Results
Sung et al. [68]	different types of (mobile) devices (including handhelds, laptop, tablet PC, cell phone, iPod or MP3 player, e-book reader, digital pen, pocket dictionary, classroom response systems and mixed)	academic achievement, sum score of affective variables	students from kindergarten, elementary school, middle school, (senior) high school, university, and graduate school; teachers, adults, and mixed	formal settings (e.g. classroom), informal settings (e.g., museum, outside), unrestricted, and not mentioned	110	- meta-analysis and research synthesis of the effects of integrated mobile devices in teaching and learning (during the period 1993–2013) - moderate mean effect sizes of $g = 0.52$ for the application of mobile devices on academic achievement and $g = 0.43$ on affective variables - moderator analyses showed greater effects for handhelds compared to laptops; more effective use in inquiry-oriented learning compared to traditional lectures, self-directed study, cooperative learning, and game-based learning; higher effects for informal compared to formal educational environments; medium- and short were superior to long-term interventions
Chauhan [14]	technologies in education (no specification of types of mobile devices)	learning effectiveness	elementary students	learning environment in general, additionally split into formal (e.g., classroom), informal (e. g., home, outside), and mixed settings	122	- meta-analysis of the effects of - the impact of technology on learning effectiveness of elementary students (based on published studies after 2000) - moderate mean effect size of $g = 0.55$ that technology leads to effective learning of elementary students. - - moderator analyses indicated greater technology effects for learning general subjects and science; higher effects for small and long during interventions; greater effects for informal settings
Cho et al. [17]	mobile devices (no differentiation of device types)	language learning achievement	kindergarten children, elementary students, primary students, secondary students, and post-secondary students	educational activities in language learning delivered via mobile devices in formal or informal learning environments	20	- meta-analysis of the effects of using mobile devices on student achievement specially in language learning (during the period 2005–2017) - moderate mean effect size of $g = 0.51$ of using mobile devices on language acquisition and language-learning achievement - - moderator analyses showed significant effect sizes only when language learning achievement was assessed using researcher-made scales
Talan [71]	mobile learning (no specification of types of mobile devices)	learning performance	students	primary school, secondary school, high school, university, and other	104	- meta-analysis of the effects of mobile learning on student performance (during the period 2009–2019) - high mean effect size of $g = 0.85$ of using mobile devices on students' academic achievement - - moderator analyses showed that the effect sizes only differed from subject
Chen et al. (2020)	mobile devices (no differentiation of device types)	language learning achievement	kindergarten children, elementary students, secondary students, and post-secondary students	classroom, unrestricted, and outdoor settings	80	- meta-analysis of the effects of using mobile devices on language learning (during the period 2008–2018) - medium-to-high mean effect size of $g = 0.722$ of using mobile devices on language learning

(continued on next page)

Table 1 (*continued*)

Study	Focused Devices	Outcomes	Sample	Learning Settings	Number of Studies	Summary of Results
						- target language skill, target language and first/second language were found - to be significant moderators

capture and retain learners' attention but might also create rule-based experiences restricting learners' sense of autonomy, creating a very school-like experience and thereby demotivating students [27]. Likewise, intensive use of class time may lead to better performance, but reduced enjoyment of learning [33]. Therefore, broadening the view on other learning-related factors beyond achievement may result in a more nuanced picture of handheld effects on these outcomes, as well as on mechanisms how and under which conditions their use and implementation enhances achievement. Fourth, there are primary studies which have examined effects of handheld use on outcomes beside achievement (e.g., intrinsic motivation, self-efficacy and satisfaction with learning:), which implies that the importance of a more nuanced consideration of outcomes has already been acknowledged. However, while there are reviews and meta-analyses summarizing the association of mobile devices with academic achievement (e.g., [68]), there is no meta-analysis to date capturing their effects on motivational outcomes and differentiated by learning design.

3.2. Categorization and selection of learning-related factors

There are multiple theories of learning and learning-related factors, each focusing on different aspects of cognitive processes, motivation, the individual, and its environment, which also overlap in some parts [57, 80]. Therefore, a selection and specification of learning-related factors for the present study is necessary. This process is guided by two pertinent frameworks on psychological learning theories and cognitive load theory ([69]; 1989) of instructional design research. First, we draw on *learner-centered psychological principles* which were formulated to provide an agenda to guide educational reform efforts [4]. The 14 learner-centered principles point to decisive factors and processes for learning, thereby placing the individual into the center of an active learning process (e.g., "Principle 3: The successful learner can link new information with existing knowledge in meaningful ways.", p. 3). These principles are categorized into research-validated domains, whereby especially the two domains "metacognitive and cognitive" and "affective and motivational" contain relevant evidence for significant learning-related factors here as they can be successfully applied to e-learning contexts [49]. Affective and motivational factors, according to these principles, comprise constructs from several motivation theories (e.g., intrinsic motivation and perceived autonomy: self-determination theory, [60]; personal value and relevance of learning: expectancy-value-theory, [78]; self-efficacy: social cognitive theory, [6, 87]). The factors addressed in these two domains are also largely found in models of *self-regulated learning* [9,86]. Self-regulated learning theories highlight that in order to learn effectively, learners first assess their appraisals of and attitudes towards a task, including their enjoyment, interest, self-efficacy, and perceived relevance of the material as necessary preconditions of engagement with the material ([86],b). These adaptive attitudes towards learning are also increasingly examined in mobile learning research (for an overview see [56]).

The two theoretical frameworks mentioned above indicate a broad range of learning-related factors relevant to examining effects of handheld use in classes. . On the one hand, these factors are already presorted by empirical selection, on the other hand, the frameworks include central factors of different more specific theories (e.g., self-determination theory, [60]; or social cognitive theory, [6]). This makes both frameworks applicable to research in the e-learning domain [49]. Additionally, we included the cognitive capacity limitations in processing information in the context of knowledge acquisition during learning [69], because learning with handhelds should also be designed to reduce learners' cognitive load (c.f. [48]). Overall, these two frameworks were examined for matching broad umbrella categories of learning-related factors that are a) directly relevant to the initiation, implementation, and completion of successful learning episodes, and b) preconceptualized and well-defined by motivational psychological theories (such as self-determination theory, social cognitive theory, or cognitive load theory). These terms are considered both theoretically and empirically useful as search terms for the meta-analysis (e.g., "intrinsic", "self-efficacy", or "cognitive load"; see method section for complete list of search terms).

3.3. Overview and definitions of learning-related factors

The final selected factors and their definitions can be obtained from Table 3. *Attitudes toward learning* reflect a person's subjective evaluation of the costs and benefits of certain behaviors [3]. Regarding academic learning, positive attitudes are characterized by high intrinsic and utility value for learning activities, that is, certain domains and subjects at school are experienced as enjoyable and useful for one's future development [23].

In research on both achievement motivation [23] and emotions [58], *satisfaction with learning* is regarded as a central adaptive outcome variable, which is desirable in its own right, but also acts as an important driver for successful learning and learning experiences [13,62]. If learners experience satisfaction during a learning process, they are more likely to seek similar learning processes in the future, resulting in above-average engagement [23].

Besides these attitudinal factors, *cognitive load* theory [70] postulates that the capacity of working memory is limited as only a certain amount of information can be processed. Therefore, learning materials should reduce the load on working memory. Reducing cognitive load, for instance by diverse presentation of learning material, has been found to enhance students' learning outcomes [46].

Additionally, four outcomes more strongly relating to motivation for studying were extracted. *Self-efficacy beliefs* describe the subjective convictions of an acting person based on their own available competence to handle difficult or new situations and challenges [6,63]. Numerous studies have shown that self-efficacy enhances resilience, motivation (regulation), and persistence in the face of adversities, while it further reduces maladaptive studying behaviors, such as procrastination (e.g., [6,35,39,83]).

Intrinsic motivation refers to learners' engagement based on their experience of the activity as being pleasant and rewarding as opposed to external pressures and rewards upon task completion [61]. These activities are perceived as meaningful, inherently interesting, and enjoyable [60]. Many studies suggest that intrinsic motivation is as important as cognitive skills and prior knowledge in predicting academic achievement and academic success (e.g., Author, 2019; [37,62]).

Experiencing *autonomy* and self-determined in learning contexts is an important prerequisite for intrinsic motivation and successful learning [60]. This basic psychological need describes the experience that one can decide on aspects relevant to one's life [61]. If human needs for autonomy are fulfilled, learners authentically engage in learning activities which is why autonomy is counted among the most important

Table 3
Operational definitions and search terms of variables included in the meta-analysis.

Included Variables	Operational Definition	Search Terms
handhelds	type of handheld device (such as mobile phones, tablets, PDAs, PMTs, pocket computers, phablets, and E-book readers (without additional technical accessories, e.g. motion-tracking sensors)	“mobile device” OR “tablet” OR “smartphone” OR “mobile phone” OR “personal digital assistant” OR “PDA” OR “pocket computer” OR “personal mobile tool” OR “PMT” OR “iPhone” OR “iPad” OR “tablet PC” OR “handheld” OR “tablet computer” OR “cell phone” OR “portable” OR “android” OR “pad” OR “class response system” OR “e-reader” OR “phablet”
Learning-related Factors		
attitude towards learning and the subject	students subjective evaluation of the costs and benefits of certain behavior [3], e.g., evaluations involving intrinsic and utility value of learning activities, but also emotional, effort and opportunity costs of engaging in academic activities form these attitudes [23].	“attitude” OR „subject“ OR „learning“
cognitive load	students’ cognitive load during learning ([69]; 1989; 1994, [81])	“cognitive” OR „cogntive load“ OR „mental“
satisfaction	satisfaction with learning (e.g. [77])	“satisfaction”
Motivational		
self-efficacy	subjective belief of a person regarding their abilities to produce desirable outcomes affecting their lives [6,87]	”self-efficacy“
intrinsic motivation	when learners act on their own initiative, and if these activities are perceived as meaningful, inherently interesting, and enjoyable [31,61]	“motivation” OR “intrinsic” OR „joy“
autonomy	Students perceived feelings of autonomy (c.f. [31,61])	”autonomy“ OR “self-determined” OR “autonomous motivation“
relevance	personal relevance of the learning (material) and subject (c.f. [78,79])	“relevance“ OR „important“
Achievement		
academic achievement	global or subject-related academic achievement (reported as grades, grade points, or specific performance tests)	“achievement” OR “test” OR “grades” OR “academic achievement” OR “learning performance” OR “grade points” OR “educational performance” OR “intelligence” OR “performance“

Notes. The full algorithm or subsets of the algorithm was used whenever possible. In some data bases, additional search terms (e.g. AND“teaching” OR “learning” OR “e-learning” OR “school” OR “university” OR “students” OR “teacher” OR “learn” OR “achieve” OR “achievement”, “app” OR “smartlet” OR “WLAN”, “outcome“; “affective”; “skills”) and the additional “NOT”- operator were added to specify the results (e.g. (health* OR pharma* OR addict* OR disorder* OR disease* OR disability* OR organic* OR illness* OR clinic* OR symptom* OR autism* OR injury* OR depression* OR rehabilitation* OR therapy* OR network* OR cyber* OR * wearables * OR robot* OR mouse* OR antenna* OR MHz* OR GHz* OR malware* OR security* OR machine learning* OR carbon* OR copper OR liquid* OR molecular* OR ion* OR nano* OR polymer* OR polar* OR temperature* OR fabrication* OR business* OR dynamic* OR rat* OR rats* OR mice* OR driver*). Initially, the search algorithm included other search terms (e.g. ”learning strategies“, ”skills“, ”self-esteem”, ”self-concept“, “self-worth”) in an attempt to identify studies that map to other psychological and learning-relevant factors, which are components of the established frameworks used in this work.

learning-related factors [20,61].

Finally, perceived *relevance* of learning material refers to the subjective importance of the material and learning for learners and its utility for their future lives [78]. Research has shown that students show better achievements when they perceive the material as personally meaningful [23].

3.4. Potential moderators of the effects of handheld use

As previous authors of meta-analyses (e.g. [68]) in this field have noted, the effect of handheld use on learning-related outcomes and achievement may depend on several factors and is not equal across different groups of learners, contexts, nor handhelds used. Such heterogeneity in effects can be explained by activity theory [5], which describes activity systems (e.g., mobile learning) as a unit of analysis and illustrates how human learning behaviour occurs depending on several factors, such as learning tools, rules, contexts, and subjects. This theory has therefore often been used in previous research about mobile learning (for an overview see [18]), for example for selecting variables moderating the relationship between mobile learning environments, achievement, and several aggregated “affective” variables (e.g., [68]), as well as for designing mobile learning environments (e.g., [89]). Since this popular theory captures the complex interactions of several factors, interindividual, and situational differences in learning it provides a useful guideline to detect which factors may explain heterogeneity in effects of handhelds on outcomes. For one, according to previous meta-analyses, the type of handheld device (referring to the “tools” component of activity theory) is a significant moderator of the effect of handheld use on achievement because technological properties may provide different opportunities for learners to engage with them (e.g., [68]). Second, learning designs in which handheld devices were used (corresponding to the “rules/control”, “objectives” and “communication/interaction” components of activity theory as a kind of teaching method) can impact effect sizes [68]. Third, duration of handheld use (corresponding to the “context” component of activity theory) may enhance effects of handheld use on learning-related outcomes due to prolonged times of engagement. However, previous meta-analyses have reported mixed results regarding this moderator (e.g., [14,68]). Fourth, subject and discipline (aligning with the “rules/control” component of activity theory) can be expected to produce differential effects of handheld use on learning-related outcomes as Sung et al. [68] found differential effects for various subjects. Fifth, origin of the sample (corresponding to the “subjects” and “contexts” components of activity theory) has not been examined by any previous meta-analysis, but is considered exploratorily in the current study. Sixth, individual characteristics of learners, such as age, gender, and level of education (referring to the “subjects” component of activity theory) have produced mixed results as moderators of effects in previous meta-analyses (e.g., [17,68]) and therefore require further investigation. These moderator analyses will further add to a more nuanced understanding of how and under which conditions handheld use enhances learning-related outcomes and achievement and are thus particularly useful for practical recommendations for educational institutions.

4. The present research

A meta-analysis on the relationship between handheld use and learning-related factors in the academic domain is clearly needed for three reasons. First and foremost, we include desirable outcomes of successful learning episodes beyond academic achievement. As outlined above, it is essential to overcome the exclusive focus on academic achievement as sole outcome variable by broadening the view on further learning-related factors [47] to better understand *how and why* handheld use affects achievement. In the present study, we therefore draw on several aspects of learners' motivation from large motivation theories [60,80,86], as well as cognitive load ([69]). All learning-related factors examined are necessary and important components in the complex and recursive process of successful learning and achievement [32,53,61,88]. If our meta-analytic results show a generally positive effect of handheld use on these learning-related factors, this would provide another strong argument to promote the use of handhelds for learning in the future. Second, the implementation of handhelds in formal educational settings continues despite a lack of clear evidence that these devices have a positive impact on motivational and cognitive factors facilitating achievement, such as self-efficacy, intrinsic motivation, or cognitive lead [72]. Although some meta-analyses have included handhelds and/or formal learning settings in their computations [68], none of them has provided an in-depth analysis of a broad range of learning-related outcomes for the specific application context of using handhelds in formal educational settings. A better understanding of how and through which psychological variables supporting academic achievement handheld use improves (or impedes) learning and achievement can help us implementing handheld use in a more adaptive manner. Third, it is still unclear whether and which differential effects can be expected from different learning designs (e.g., teacher-centered lectures and classes vs. self-directed and self-regulated learning – see Table 2 for the categorized learning designs occurring in this study) in which handhelds are used. Fourth, as previous work (e.g., [68]) suggests, there is considerable heterogeneity in specific learning designs and teaching methods using such devices. It is still unclear whether and which effects can be expected from different learning designs (e.g., teacher-centered lectures and classes vs. self-directed and self-regulated learning) in which handhelds are used. However, such findings are needed in the long term to provide unambiguous guidelines for practitioners on how to best implement and use handhelds in their teaching in the future [72].

Therefore, we conduct a meta-analysis on the effects of handheld use on motivational and other (cognitive load, satisfaction with learning, attitude towards learning and subject) learning-related factors (as well as academic achievement for update purposes) in formal educational settings. We aim to explore the mean effect sizes of handheld use as well as specific learning designs in which handhelds are used on these outcomes, and additionally, the possible influences of moderating variables. Fig. 1 graphically illustrates our assumed theoretical relationships and what we are investigating in this meta-analysis.

5. Methods

5.1. Data sources and literature search

Searches were conducted in psychological bibliographic subject databases (PUBPSYCH, PSYNDEX, PsychOpen, PsychData, and PsycINFO) and an educational bibliographic subject database (PeDOCS). Furthermore, multidisciplinary bibliographic databases (Google Scholar and Web of Science) were searched. Grey literature such as project documentations, dissertations, and conference papers were also integrated in the search process. A flowchart representing the entire literature search and review process is shown in Fig. 2.

If possible, data bases were searched using search algorithms combining keywords for handhelds and outcomes such as intrinsic motivation, self-efficacy, or cognitive load via operators (see Table 3 for included variables, operational definitions and search terms). Several electronic devices (e.g., wearables) and contexts (e.g., business, health) not included in the current study were excluded via NOT-operators. In addition, we manually searched the reference-lists of selected articles, relevant reviews, and meta-analyses (e.g., [14,17,19,38,40,68,72,73,84]). We further explored the table of contents in relevant topic-related journals (Computer & Education, British Journal of Educational

Table 2
Sample characteristics of included studies.

coding year of publication	k	%	coding country of origin	k	%
1998 - 2005	0	0	USA	10	18.6
2006 – 2010	07	11.9	Germany	1	01.7
> 2011-2020	52	88.1	Taiwan	17	28.8
document type			China	4	06.8
peer-rev. journal articles	54	91.5	Turkey	3	05.1
publications in conference proceedings (former conference papers)	05	8.5	Jordan	3	05.1
dissertation / master thesis	00	0	Norway	1	01.7
unpublished / manuscript data	00	0	Greece	3	05.1
educational level			Spain	3	05.1
elementary school	20	34.0	Scotland	1	01.7
secondary school	23	39.0	Iran	1	01.7
university/ college	16	27.1	Cyprus	1	01.7
mean age (students)			Malawi	1	01.7
< 10 years	10	17.0	Singapore	1	01.7
11 – 15 years	20	35.6	Malawi	1	01.7
16 – 20 years	13	22.0	South Korea	1	01.7
< 20 years	04	06.8	Kuwait	1	01.7
unknown	11	18.6	Israel	1	01.7
sample size			Mexico	1	01.7
$N < 50$	20	35.6	Netherlands	1	01.7
$N = 51 – 100$	30	50.9	Singapore	1	01.7
$N = 101 – 150$	03	05.1	**funding of the study**		
$N = 151 – 200$	04	06.8	university	08	13.6
$N = 200$	01	01.7	company	01	01.7
gender (percentage of female participants)			government support	12	20.3
< 25 % female	01	01.7	foundation	02	03.4
26 – 50 % female	11	18.7	other	02	03.4
51 – 70% female	16	27.1	unknown	34	57.6
71 – 100% female	04	06.8	**overall duration of use (mean: hours per week)**		
not identified	27	45.8	< 25 h	20	34.00
language			26 – 50 h	02	3.4
English	59	100	51 – 75 h	00	0
German	00	00	76 – 100	02	3.4
			unknown	35	59.3
material and device type of the control group			**type of handheld**		
regular classes/ courses	30	50.9	tablet und phablet	27	44.8
paper-based material	22	37.3	cell phones / smartphone	23	39.7
computer	2	03.4	personal digital assistant (PDA)	04	06.9
no control group	2	03.4	e-Book reader	01	01.7
unknown	3	05.1	derived/ mixed	04	06.9
school subject			**university subject / higher education domain**		
biology	4	09.3	foreign language	7	43.8
social science	1	02.3	history	1	06.3
foreign language	10	23.2	sociology	1	06.3
language (mother tongue e.g., English, Spanish)	2	04.7	teacher post	1	06.3
mathematic	7	16.3	art	1	06.3
physics	4	09.3	biology	2	12.5
natural science and technic	6	10.2	business administration	1	06.25
psychology	1	02.3	**study design**		
history	2	04.7	experimental study with pre- & posttest, TG + CG group	0	0
geography	3	07.0	quasi-experimental study with pre-& posttest, TG & CG	44	74.6
music	1	02.3	experimental study witch pre & posttest, only TG	01	01.7

(*continued on next page*)

Table 2 (*continued*)

coding year of publication	k	%	coding country of origin	k	%
religion	1	02.3	quasi-experimental study with pre-& posttest, only TG	02	03.4
mixed	1	02.3	experimental study only posttest, TG & CG	00	0
learning design TG			quasi experimental study only posttest, TG & CG	12	20.3
lectures and classes	5	8.5	experimental study only posttest, only TG	0	0
inquiry-oriented learning	7	11.9	quasi-experimental study only posttest, only TG	0	0
cooperative und peer learning	4	6.8	**kind and type CG**		
self-directed and self-regulated learning	11	18.6	general teaching and learning with handhelds or other devices	2	3.4
mixed	19	32.2	general teaching and learning without handhelds	39	66.1
other/ cannot be classified	9	15.3	learning with devices teaching strategy in lectures or learning with devices teaching strategy Inquiry-oriented learning or others	2	3.4
unknown	4	6.8	mixed	4	6.8
			other/ cannot be classified	7	11.9
			unknown / no CT	5	8.5
learning design CG					
learning design reported – lectures and classes	18	30.5			
one specific learning design reported	7	11.9			
other/ cannot be classified	8	13.6			
mixed	8	13.6			
unknown	18	30.5			

Notes. Bold words represent variable names; k = number of included samples; CG = control group; TG = treatment or experimental group; percentages not adding up to 100 are due to rounding.

Technology, Computers in Human Behavior, Internet, and Higher Education, Knowledge Management & E-learning, Journal of Computer Assisted Learning, German Journal of Educational Psychology, and German Journal of Developmental and Educational Psychology). Moreover, we personally contacted several known authors in the field and requested previously inaccessible full texts, unpublished studies, and unpublished data that matched the aforementioned search terms.

5.2. Eligibility criteria

The initial search procedure led to the identification of 12,939 potentially relevant studies of which 11,859 remained after duplicates were removed (see Fig. 2). Eligibility criteria for these remaining studies were a) types of handheld devices, such as mobile phones, tablets, PDAs, PMTs, pocket computers, phablets, and E-book readers (without additional technical accessories, e.g. motion-tracking sensors) were explicitly reported and used for learning; b) relations of handheld use with academic achievement (operationalized as grades, grade points, or specific performance tests) or with learning-related factors (e.g., intrinsic motivation) or with both academic achievement and learning-related factors were reported; c) handheld use occurred in formal educational settings (i.e., the handheld is used in the context of the education system, in direct connection with places such as schools and universities); d) the sample comprised learners in educational institutions of the first educational path; e) the publication period ranged from 1998 to January 2021; f) the study was written in English or German; g) the study had an experimental or quasi-experimental research design, with a pre-test, post-test, or both, and included at least one treatment group and one or more control groups with preferred use of conventional teaching, paper-based materials, or any type of mobile devices; h) the work provided statistical information to calculate the effect size Hedges g (e.g., such as means, standard deviations, t-values, F-values, sample size for each group).

Accordingly, studies were excluded if students used laptops, computers, desktop-PCs, notebooks, or convertibles, Hybrid-PCs, digital pens, and other portable media devices, such as game consoles, navigation devices, calculators, and wearables. If handheld use occurred mainly during leisure time or in private lessons, the study was excluded, as well as when samples comprised kindergarten children, pre-school children, or persons on the second educational pathway. Another reason for exclusion was if handhelds were used exclusively for specific groups of learners (e.g., those with learning disabilities or medical conditions). Ubiquitous and multi-handheld use was not an exclusion criterion, provided that the handheld types and their use were matched with the eligibility criteria. After classification and coding, 58 studies with 59 samples were included in the meta-analysis. Table 2 shows their formal, content, and methodological study characteristics, as well as the coding categories that were documented in a detailed coding manual.

To ensure a high reliability of study coding, a random selection of just under 20% of the 58 studies were additionally coded by a second rater. When substantial differences in coding occurred, both coders discussed the case and corrected the respective coding where necessary. Except for two variables, interrater reliabilities were excellent (see ESM, Table 1). An overview of the sample characteristics of all the studies and the coding categories is given in Table 2.

The rigorous inclusion criteria described are intended to enhance the quality and validity of the meta-analysis presented here. In this context, it is also important to ask which instruments were used to generate the findings in the included primary studies. Of particular interest is whether reliable and valid measurement instruments were used (compared to non-validated "home-grown" surveys). In order to take this aspect into account, the studies with one or more learning-related factors as outcomes were examined to see whether there was evidence of reliability and validity and even norm data for the instruments used in the respective study. The findings show that, with very few exceptions, convincing evidence for the reliability and validity of the questionnaires used was reported (see ESM, Table 2). With regard to reliability, the reported cronbach's alphas or composite reliabilities were almost always above the cutoff of .70, often even significantly higher. With regard to validity, it was found that frequently established questionnaires that had been sufficiently validated in previous studies were used, e.g., MSLQ in the study by Rachels and Rockinson-Szapkiw or the SMQ in the study by Nikou and Economides . In contrast to the often available reliability and validity evidence, questionnaires providing norm data were rarely used.

5.3. Effect size calculation and sensitivity analyses

If the target effect size Hedges' g was not reported directly in the study, the effect size d, or available statistical parameters (e.g., means, standard deviations, and sample sizes for each pretest and posttest, and control and treatment groups) were used for calculation. If studies provided results for more than one measurement point, the effect size g or d for comparing the pre- and posttest results of the respective variable was considered. If one study comprised multiple control groups (e.g., computer-based and paper-based material) we included the control group that used the more traditional and "analogous" material and devices to obtain stochastic independence of included effect sizes.. If results in one study reported two effect sizes g for one dependent variable (e.g., academic achievement), but for two independent samples, we used both information for mean effect size calculation.

The calculation of effect sizes and all further statistical analyses were

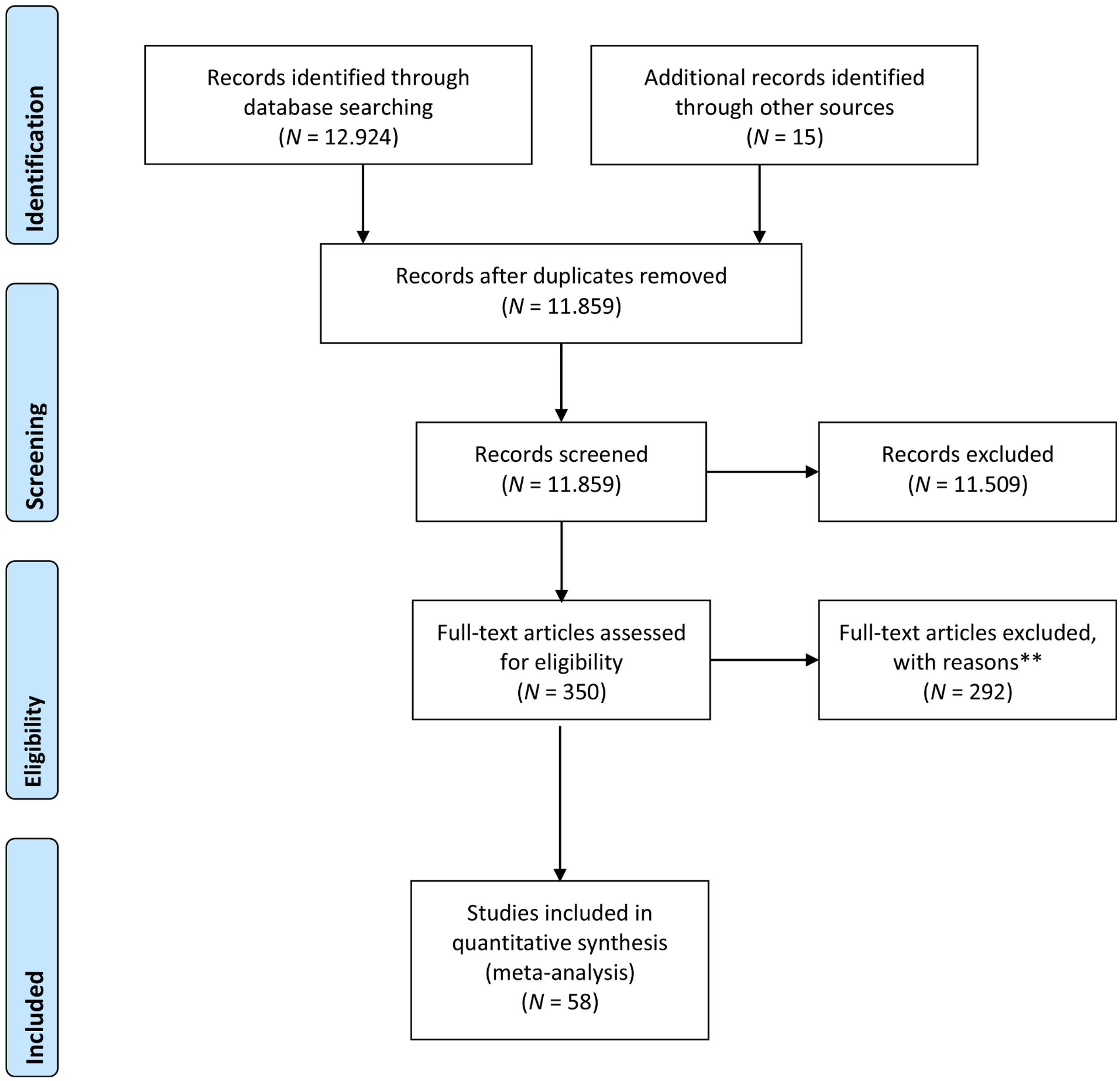

Fig. 2. PRISMA Flow Chart of Literature Search and Study Selection.
Note. ** Exclusion based on multiple criteria possible and for the following reasons: $N = 93$ statistical information, $N = 62$ research design, $N = 47$ operationalization / other investigated variables, $N = 49$ type of handheld unclear or not match, $N = 31$ context, $N = 22$ sample, $N = 14$ no access to full-text, $N = 4$ other (language, tech. accessories).

conducted via the Comprehensive Meta-Analysis (CMA) software version 3 by Borenstein et al. [11]. Regarding the total effect, the effect sizes were integrated using the random effects model (REM) which allows for differences in treatment effects across studies. The restricted maximum likelihood (REML) estimator was chosen for its robustness and efficiency, I^2 statistics and Cochran's *Q*-Test were considered as measures for heterogeneity (see [10], for an explanation of these statistical measures in meta-analyses). Potential publication bias was tested threefold. First, we identified effect sizes with studentized residuals of $\pm$ 1.96 as potential outliers [76]. However, we only excluded those effect sizes if theoretically justified. Second, we conducted visual checks of asymmetrical funnel plots [67] which may indicate a bias of included samples in meta-analysis. Third, we computed rank correlation tests and regression tests that both provide statistical measures of funnel plot asymmetry [67].

5.4. Moderator analyses

Building on activity theory [5] and previous meta-analyses (e.g., [68]), the following moderators were examined: type of handheld device, learning designs, duration of handheld use, subject and discipline, origin of the sample, as well as individual characteristics such as age, gender, and level of education. These respond to activity theory's categories of "tools", "rules/control", "context", and "subjects" [5]. To additionally consider technological advances in handhelds over time, publication year was included as a further explorative moderator (e.g., [2,51]).

The meta-analytic mixed effects model (MEM; see [10], for explanation) was used to investigate the presumed moderation effects. The categorical moderators type of handhelds (cf., components of activity theory; [5]), level of education, and origin of sample were analyzed with a weighted meta-analytic analogue to variance analysis. Univariate meta-regressions were conducted for the continuous moderators gender, age, and duration of handheld use.

6. Results

6.1. Descriptive statistics of included studies

The 58 included studies compromised a total of $N = 4{,}259$ participants (range: 9 to 277). All studies were published between 1998 and January 2021, and came mainly from Asia (39%), the Middle East (20.3%), Europe (18.6%), North America (18.6%), and Africa and South America (1.7% each). The samples represented mainly elementary and high school students (72.1%), but also higher education and university students (27.1%). Participants' average age was between 11 and 15 years (approx. 36%). Approximately 17% were younger, while 22% were between 16 and 20 years, and about 6% were more than 20 years. Tablets (approx. 44%) and cell phones (approx. 39%) were the most frequently examined handhelds across included studies. Most frequently, "different learning designs" (at least 2 different ones) were used in the treatment group, closely followed by only used "self-directed and self-regulated" learning-design. Across both educational levels, results showed that handheld use was investigated across various subjects albeit more frequently in the context of foreign language learning (school: 23.26%; university: 43.75%). In approximately 75% of the cases, a quasi-experimental study design with a pre- and post-test, experimental, and control groups was applied. A quasi-experimental study design without a pre-test, but with a post-test and experimental and control groups represented the most frequently chosen design with approximately 20% of the included studies. Only one included study showed an experimental study design. Among the studies with a control group, approximately 51% of the participants received conventional teaching, while about 37% of the cases used special paper-based learning materials. More than half of all studies realized a comparison of the treatment group with general teaching and learning without handhelds as the control group. For one third of the included studies, information about the control group's learning design was missing. For the majority of the studies (approx. 58%), it is unknown where the funding (mainly for the technical equipment) of the studies came from, while almost 20% received state financial support. Further details on sample characteristics are displayed in Table 2. The overall effects of handheld use on all outcomes are shown in Table 4.

6.2. Overview of learning-related factors identified in included studies

Because the search strategy involved theoretically rather broad umbrella categories, the studies included in the meta-analysis were first screened in more detail to more accurately determine the learning-related factors included. Overall seven learning-related factors were identified while there were separate ones for attitude toward learning and the subject, $k = 7$, cognitive load, $k = 4$, satisfaction with learning and subject, $k = 7$, and four motivational factors (self-efficacy, $k = 6$; intrinsic motivation, $k = 5$; feelings of autonomy, $k = 3$; relevance of the learning material and the subject, $k = 3$). For the sake of greater clarity, the learning-related factor in question will be briefly defined and classified at the beginning of the respective result subsection. A broader theory-based interpretation is then provided in the discussion.

6.3. Attitude toward learning and the subject

Handheld use showed a significantly positive, moderate total effect of $g = .44$ ($z = 4.35$, $p < .001$; g range = -.01 to .69, 95% CI [.24, .64]; $k = 7$) on learners' attitude toward subject or learning content. The sensitivity analysis revealed one study as a potential outlier according to the studentized residual of $z = -2.07$. However, we found no indication that study-specific characteristics, or other reasons, could explain the inconsistent outliner of this study compared with the other included studies. Therefore, this study was not excluded. Fig. 5, ESM, displays the forest plot of the included studies. An inspection of the funnel plot in Fig. 10, ESM, did not point to any asymmetrical distribution. Neither the rank correlation test (Kendall's $\tau = -.09$, $p = .76$), nor the regression test ($b_0 = -.23$, $p = .89$) indicated a funnel plot asymmetry. The non-significant result of the Cochran's Q-Test ($Q = 6.13$, $df = 6$, $p = .41$, $I^2 = 2.18\%$) suggests absence of heterogeneity in included effect sizes

6.4. Cognitive load

The random-effects model yielded an estimated total effect of $g = -.47$ ($z = -2.34$, $p < .05$; g range = -.76 to .08, 95% CI [-.87, -.08]; $k = 4$) of handheld use on cognitive load. This indicates a negative and significantly moderate effect size, indicating that the cognitive load of learners was moderately reduced by handheld use. The external studentized residuals were all within ±1.96 [76]. Therefore, they did not indicate any outlier studies (funnel plot see Fig. 11, ESM). Due to the small number of studies ($N = 4$) the funnel plot inspection indicated asymmetry. However, neither the rank correlation test (Kendall's $\tau = -.83$, $p = .09$), regression test ($b_0 = -17.52$, $p = .16$), nor trim-and-fill method [21] results confirmed this conclusion. Cochran's Q-Test suggested heterogeneity ($Q = 7.06$, $df = 3$, $p = .05$), indicating that there were differences among the true effects. The amount of total variability between the observed effect sizes due to heterogeneity was $I^2 = 60.54\%$ and thus classified as moderate. However, due to the small number of available studies, the heterogeneity could not be clarified in further moderation analyses.

6.5. Satisfaction with learning

There was a significantly positive and high total effect of handheld use in a formal context on satisfaction with learning of $g = .77$ ($z = 8.97$, $p < .01$; g range = .49 to 1.11, 95% CI [.603, .940]; $k = 7$). No potential outliers were found (see Fig. 4, ESM for the forest plot). A visual inspection of the funnel plot (see Fig. 9, ESM) was not representative due to the small number of included samples. Neither the rank correlation test (Kendall's $\tau = -.191$, $p = .55$), nor the regression test ($b_0 = -2.49$, p

Table 4
Overall effect sizes for all outcomes.

Outcomes	ES	SE	95 % CI	K	N	z	Q	I^2
attitude	.44***	0.102	[.244; .644]	7	334	4.35	6.13	2.18 %
cognitive load	- .76*	0.201	[-.865; -.076]	4	257	- 2.34	7.06*	60.54 %
satisfaction	.77 ***	0.086	[.603; .940]	7	474	8.97	5.68	0.00 %
Motivational								
self-efficacy	.52**	0.166	[.192; .841]	6	427	3.12	15.48**	67.69 %
intrinsic motivation	.55***	0.225	[.303; .795]	5	214	4.37	4.57	12.39 %
autonomy	.68**	0.232	[.221; 1.130]	3	169	2.91	6.37*	68.59%
relevance	.41**	0.136	[.143; .677]	3	233	3.01	2.13	6.24%
academic achievement	.71***	0.074	[.563; .854]	55	2151	9.55	290.04***	81.38 %

Notes. ES = average g ($\hat{\mu}_\rho$); estimated mean of the true effect sizes; SE = standard error; CI = lower and upper limits of 95% confidence interval; k = number of included samples/ effect sizes; z = z test for significance; Q =heterogeneity index with df = k−1; I^2 = proportion of variance of true effect sizes in the overall variance of observed effects in %; N = number of included participants. * $p < .05$, ** $p < .01$, *** $p < .001$.

= .32) indicated a funnel plot asymmetry and thus no publication bias. The non-significant result of the Cochran's Q-Test ($Q = 5.68$, $df = 6$, $p =$ .46) and the I^2 value of 0.00% suggested absence of heterogeneity, indicating no need for further moderation analyses.

6.6. Motivational factors: Self-efficacy

Handheld use showed a significantly positive, moderate total effect of $g = .52$ ($z = 3.122$, $p < .01$; g range = -.01 to .81, 95% CI [.192, .841]; $k = 6$) on learners' self-efficacy. The sensitivity analysis revealed no potential outliers based on studentized residuals [76]. A forest plot of the included studies is given in Fig. 1, ESM. The funnel plot (Fig. 8, ESM) should not be interpreted due to the small number of studies. However, neither the rank correlation test (Kendall's $\tau = .13$, $p = .71$), nor the regression test ($b_0 = 4.23$, $p = .14$) indicated funnel plot asymmetry. Thus, there was no hint of publication bias. Additionally, according to the fail-safe method [55], no distortion of publication was assumed (z observed = 5.32015 > z-alpha = 1.95996; mean g in missing studies = .000). Only the result from the trim-and-fill test [21] indicated a publication bias. Three effect sizes had to be added to achieve symmetry of the funnel plot. However, this method may be distorted in this case due to the small number of studies. Cochran's Q-Test ($Q = 15.48$, $df = 5$, $p =$ .005) suggested heterogeneity in true effects. The amount of total variability between the observed effect sizes was moderate ($I^2 = 67.70\%$). Due to the small number of studies, it was not possible to explain this heterogeneity of effects through moderation analyses.

6.7. Motivational factors: intrinsic motivation

One study was identified as a potential outlier based on studentized residuals and the investigated forest plot (see Fig. 2, ESM). In addition, the existence of a large degree of heterogeneity ($Q = 18.72$, $df = 5$, $p =$ .001; $I^2 = 74.66\%$) also supported the exclusion of the study, and all analyses were conducted again without it. After recalculation, the random-effects model yielded an estimated total effect of handheld use on intrinsic motivation ($g = .55$, $z = 4.373$, $p < .001$; g range = .30 to 7.9; 95% CI [.303, .795]; $k = 5$). Next, we tested whether this moderate mean effect size was influenced by publication bias. Due to the small number of studies, funnel plot inspection likely yielded false results. Thus, statistical estimates were primarily considered. Neither the rank correlation test (Kendall's $\tau = 1.33$, $p = .71$), nor the regression test ($b_0 = .67$, $p = .83$) indicated a funnel plot asymmetry. The fail-safe analyses [55] indicated no publication bias (z-observed = 6.66 > z-alpha = 1.96; mean g in missing studies = .000). Similarly, the non-parametric iterative method conducted by Duval and Tweedie [21] did not indicate any effect size to be added. Thus, there were no indications that the findings were biased. The non-significant Cochran's Q-Test ($Q = 4.565$, $df = 4$, $p =$ .335), as well as a low value of $I^2 = 12.39\%$, suggested no heterogeneity. Overall, these findings uniformly suggest that the previously large heterogeneity was caused exclusively by the outlier study, and not by other study-specific characteristics.

6.8. Motivational factors: feelings of autonomy

The random-effects model showed an estimated total effect of $g = .68$ ($z = - 2.91$, $p < .01$; g range = .20 to 1.13, 95% CI [.221, 1.130]; $k = 3$) regarding the effect of handheld use on learners' feelings of autonomy. This represents a significantly positive and high effect. A forest plot of the included studies is shown in Fig. 3, ESM. However, due to the small number of studies, no reliable estimates of publication bias can be computed and are thus not reported. Also, moderation analyses could not be conducted, leaving the high heterogeneity ($Q = 6.37$, $df = 2$, $p =$ .004; $I^2 = 68.59\%$) unexplained.

6.9. Motivational factors: relevance of the learning material and subject

The random-effects model yielded an estimated total effect of $g = .41$ ($z = 3.01$, $p < .01$; g range = .18 to .62, 95% CI [.143, .677]; $k = 3$) for handheld use on perceived relevance of the learning material and subject. No outliers were identified on the basis of the sensitivity analysis. All external studentized residuals were within the limits of ± 1.96 [76]. A forest plot of the included studies is given in Fig. 6, ESM. Due to the small number of studies, publication bias analyses could not reliably be computed. Cochran's Q-Test suggested low heterogeneity ($Q = 2.133$, $df = 2$, $p = .334$), confirming the null hypothesis that the variance of the included effects is zero [34]. The I^2 statistics revealed that the heterogeneity in true effect sizes was small ($I^2 = \; = 6\%$).

6.10. Achievement factor: academic achievement

In order to explore potential mechanisms how handheld use affects learning-related outcomes and achievement, several moderators influencing this effect such as type of handheld, learning design, learner characteristics and study characteristics were examined in the present study. With regard to academic achievement, we identified and thus excluded four studies as potential outliers based on studentized residuals (two studies were above +1.96: and two studies were below -1.96;). A forest plot of the included studies is illustrated in Fig. 7, ESM. The random-effects model yielded an estimated total effect of $g = .71$ ($z = 9.548$, $p < .001$; g range = -.62 to 2.62, 95% CI [.56, .2.62]; $k = 55$) of handheld use on academic achievement in formal settings. This represents a large positive effect size as suggested by Hattie [32]. Regarding potential publication bias, an inspection of the funnel plot in Fig. 12, ESM, showed that the individual effects were not asymmetrically distributed around the estimate of the mean of the true effects. Neither the rank correlation test (Kendall's $\tau = 1.09$, $p = .24$), nor the regression test ($b_0 = 0.02$, $p = .98$), indicated funnel plot asymmetry, indicating no publication bias. Cochran's Q-Test suggested heterogeneity ($Q =$ 290.04, $df = 54$, $p =$ .001) that could be classified as large ($I^2 = 81.38\%$). Therefore, we tested whether moderators explain this heterogeneity.

When considering learning designs of TGs (categories of learning designs are displayed in Table 2), descriptively larger effect sizes compared with the overall effect of $g = .71$ were found when only studies with inquiry-oriented learning ($g = .99$, $z = 6.94$, $p < .001$; 95% CI [.712, 1.272]; $k = 5$) or studies with a mixed learning design ($g = .82$, $z = 7.10$, $p < .001$; 95% CI [.592, 1.043]; $k = 17$) were included in the analyses. In comparison, the overall effect sizes of the other learning design categories were descriptively smaller ($g = .55$ - .61). However, as reported in Table 6 (also displaying information of these separate and specific analyses regarding learning design), all confidence intervals overlap with each other, so these differences are not statistically significant.

Across all studies, four handheld device types were distinguished. However, they did not yield significantly different effects on achievement (see Table 5). No significant moderating effects were observed for origin of the samples, whereby some origins contained few samples (i.e., Africa and South America). Educational level as another potential moderator showed high effect sizes for university students ($g = .83$), compulsory school students, primary school students ($g = .72$), and secondary school students ($g = .62$). However, the Q-index did not reach significance ($Q = 1.69$, $p = .43$). A similar pattern of results emerged with regard to the moderators year of publication and learning design of CG: the Q-index did not reach significance in each case (year: $Q = .16$, $p = .69$) and (learning design: $Q = 1.04$, $p = .98$). Across all included studies, 14 school and university subjects and higher education domains were coded for primary and secondary school students, and eight subjects were coded for university students. For the moderation analysis, these were grouped into three subject groups (natural science, social and arts, and languages). No significant effects were obtained regarding the moderating subject and discipline (Table 5). Neither age

Table 5
Results of moderator analyses for the effect of handhelds on academic achievement.

Moderator academic achievement	k	ES	SE	95 % CI	z	Q
type of handheld						
cell phones	21	.77***	.09	[.578; .966]	7.82	72.74
tablets	21	.66***	.09	[.470; .859]	6.69	84.20
response system devices	1	*excluded due to too small k or could not explain variance and were removed from the model and further analysis*				
PDA	4					
e-book	0					
origin of the sample						
Asia	22	.74***	.09	[.470; .859]	8.08	52.58
Europe	9	.76***	.14	[.492; 1.041]	5.50	35.99
Middle East	11	.70***	.13	[.439; .954]	5.49	30.20
North America	7	.50***	.15	[.200; .803]	3.26	23.05
Africa	1	*excluded due to too small k*				
South America	1					
educational level						
university students	14	.83***	.12	[.582; 1.069]	6.65	36.06
primary school students	17	.72***	.10	[.512; .937]	6.68	63.26
secondary school students	20	.62***	.12	[.423; .818]	6.15	75.37
subject / domain groups						
natural sciences	24	.73***	.09	[.549; .897]	8.13	59.63
social and arts	10	.78***	.14	[.549; .897]	5.72	42.48
languages	16	.61***	.11	[.389; .835]	5.53	55.62
publication year						
1998-2005	0	*analyses could not be calculated due to too small k*				
2006-2010	7	.79***	.16	[.456; 1.116]	4.67	18.27
2011-2020	42	.71***	.06	[.578; 0.848]	10.379	144.70
learning design TG						
lectures and classes	5	.55***	.19	[.168; .925]	2.83	2.19
inquiry-oriented learning	5	.98***	.19	[.607; 1.362]	5.11	8.42
cooperative and peer learning	3	.62***	.25	[.122; 1.117]	2.44	7.34
self-directed and self-regulated learning	10	.67***	.15	[.379; .958]	4.53	19.01
mixed	17	.83***	.11	[.622; 1.036]	7.85	68.95
other/ cannot be classifed	5	.55***	.19	[.175; .931]	2.87	22.13
unknown	4	.69***	.23	[.243; 1.135]	3.03	8.65
moderator	*k*	unstandardized *b*	*SE*	*p*-value	*F* and *df*	R^2
age	42	.01	.02	.73	*F*(1,40) = .12	0.00 %
gender	25	- .01	.00	.44	*F*(1,23) = .62	0.00 %
duration of handheld use	18	- .00	.01	.96	F(1,16) = .00	0.00 %
self-efficacy, intrinsic motivation, feelings of autonomy, satisfaction with learning, attitude towards learning and the subject, cognitive load and relevance of the learning material and subject						
moderator analyses were not possible due to too small k or the investigated moderators could not explain differences in the variances of the effects						

Notes. *k* = number of included effect sizes, *ES* = mean effect size *g; SE*= standard error; KI = lower and upper limits of 95% confidence interval, *z* = *z*-test for significance for *g; Q* =heterogeneity estimate; *F* and *df* = test value with *df* = *k*-1, R^2 = proportion of variance of true effect sizes in the overall variance of observed effects in %. * *p* < .05, ** *p* < .01, *** *p* < .001.

Table 6
Overall effect sizes for all outcomes – studies summarized exclusively by learning design in the treatment group (TG).

outcomes	ES	SE	95 % CI	k	z	Q	I^2
Studies only included with learning design “mixed”							
academic achievement	.82***	.12	[.592; 1.043]	17	7.10	69.17***	76.87 %
studies only included with learning design “self-directed and self-regulated learning”							
academic achievement	.65***	.13	[.396; .910]	10	4.98	19.03*	52.71 %
studies only included with learning design “lectures and classes”							
academic achievement	.55***	.10	[.345; .754]	5	5.26	02.19	00.00 %
studies only included with learning design “cooperative and peer learning”							
academic achievement	.61*	.28	[.075; 1.158]	3	2.23	7.31*	72.63 %
studies only included with learning design “inquiry-oriented learning”							
academic achievement	.99***	.14	[.712; 1.272]	5	6.94	8.66	53.83 %
studies only included with learning design “other/ cannot be classifed”							
academic achievement	.55***	.25	[.067; 1.030]	5	2.23	22.15***	81.94 %
self-efficacy, intrinsic motivation, feelings of autonomy, satisfaction with learning, attitude towards learning and the subject, cognitive load and relevance of the learning material and subject							
overall effect size analyses could not be calculated due to too small k							

Notes. Usual moderator analyses (see Table 4) could not be conducted for the factor "learning design" due to content and methodical reasons (necessary distinction between learning design of the TG and CG, lack of information and missing statistical characteristics about learning design in the studies – especially for learning design of CG). Therefore, for each analysis, only the studies of one learning design were included and the respective overall effect sizes were calculated separately. The results of these analyses are presented in this table. Studies with learning design of TG "unknown" could not be included in this analysis for content reasons. Our used categorisation of the learning designs are guided by the categorisations of the similar moderator "teaching method" in the meta-analysis by Sung et al. [68]. *ES* = average *g* ($\hat{\mu}_\rho$); estimated mean of the true effect sizes; *SE*= standard error; CI = lower and upper limits of 95% confidence interval; *k* = number of included samples/ effect sizes; *z* = *z* test for significance; *Q* =heterogeneity index with df = k−1; I^2 = proportion of variance of true effect sizes in the overall variance of observed effects in %; * *p* < .05, ** *p* < .01, *** *p* < .001.

(unstandardized b = 0.01, *p* = .73), nor gender (unstandardized b = -0.00, *p* = .44), nor the total duration of handheld use (unstandardized b = - 0.00, *p* = .96) significantly moderated the effect of handhelds on achievement.

7. Discussion

This meta-analysis was conducted to examine the impact of handheld use on learning-related factors in formal educational settings to broaden our understanding of the effects beyond academic achievement (Fig. 1, path c). Additionally, we sought to clarify under which circumstances handheld use produces stronger or weaker effects on these outcomes. Filling this important research gap allows for a more nuanced evaluation of the opportunities and risks of the widespread and still growing use of handhelds in education and understanding how they affect learning as an active, self-directed process [72].

7.1. Effects of handheld use on learning-related factors and academic achievement

As expected, moderate to high effect sizes were found for the seven identified learning-related outcomes. Students who use handhelds in class have higher confidence in their own abilities (self-efficacy), are more intrinsically motivated for learning, feel more autonomous and self-determined, are more satisfied with learning itself, have more positive attitudes towards learning, and can see more relevance and meaning for their own lives in it. In addition, the use of handhelds seems to be helpful in reducing cognitive load. This is in line with suggestions from Mayer [46] who described that when information is presented in different ways, it can be better processed and learned. This can be achieved within the framework of media-supported learning, since the content can be presented via images, but also via words and thus acoustically and visually. Clark, Nguyen, and Sweller (2006) similarly argued that the working memory is optimally utilized through the combination of visual and acoustic performances, so that attention is better controlled and distraction is reduced.

Although all mean effect sizes are based on only a small number of primary studies, the findings nevertheless point in a consistent direction: the use of handhelds in formal educational settings seems similarly strongly associated with a broad range of adaptive learning-related factors. This is in line with theoretical propositions of activity theory [5] and self-regulated learning theories [57,86] that successful learning consists of more than just high scores on achievement tests [8,47,72], as well as results by Sung et al. [68], who found an overall moderate positive effect of mobile devices on affective variables ($g = 0.43$). The present meta-analysis adds more detail to our understanding of which learning-related factors handhelds improve to which degree.

Furthermore, our findings revealed that the effect of handheld use on academic achievement was highly positive, indicating that using cell phones, tablets, and other handhelds in class enhances performance in educational institutions. This finding is consistent with meta-analytic results from Cho and colleagues [17] and Sung et al. [68]. While it is helpful and encouraging that our findings are identical to those of earlier research, our meta-analysis provides a) novel evidence regarding outcomes of handheld use besides performance and b) methodologically sound and empirically robust evidence for the positive effects of handhelds in academic educational contexts. Notably, methodological shortcomings of previous meta-analyses such as considering the quality of the included primary studies (e.g., missing statistical information, unclear control groups, lacking operationalization of investigated variables) were resolved to some degree. The reported results describe only direct effects of handheld use on both learning-related factors and academic achievement. However, the outcome variables examined here represent an interwoven nomological network of adaptive learning-related attitudes and behaviors. Decades of research have shown, for example, that motivational factors are among the most important predictors of academic achievement (e.g., [66]). As illustrated in Fig. 1, these factors function as decisive mediators of handheld use on academic success. This demonstrates that the positive influence of one component of this network can result in a positive cascade for all outcomes, like a domino effect [32]. However, it is clear from the primary studies examined here that some digital interventions in the classroom may not always directly lead to better performance. Hochberg and colleagues, for example, found that learning central paradigms in physics via cell phone tools enhanced students' intrinsic motivation, but it was not directly associated with physics exam scores. However, increased intrinsic motivation increases knowledge acquisition which in turn would be supposed to boost students' performance in the long run [23]. Those positive recursive cycles have also been reported for other learning-related factors like, for example, self-efficacy [23] and achievement emotions such as satisfaction ([58], see also [62,66]). Therefore, the present study highlights the necessity of a broader view of the possible positive effects of handheld use, as well as an examination of causal and temporal dynamics of handheld use on academic achievement via, for example, motivational variables.

In line with learner-centered psychological principles and theories of self-regulated learning [9,86], the present meta-analysis provides a comprehensive picture of empirical evidence indicating that the use of handhelds in classrooms is associated with adaptive motivational-affective attitudes and experiences. However, these models also emphasize the dynamic and process-oriented nature of the learning process which, besides adaptive motivational and affective preconditions, require the setting of adequate learning goals, monitoring of goal progress, and the use of cognitive, metacognitive, and motivational regulation strategies [59,86]. For example, it can be assumed that the technical possibilities of handhelds are helpful in setting suitable learning goals and goal monitoring (e.g. via increased and individualized opportunities for feedback on the learning progress), or implementing metacognitive control (e.g., reflecting on one's own learning process through regular reminders), which could then emerge more quickly and better as a skill in students through model learning. The degree to which the positive effects on academic achievement are mediated via specific learning processes cannot be investigated in more detail in this study due to the low statistical power. Future studies should therefore further investigate this question with appropriate designs. Additionally, longitudinal investigations are needed to examine potential differences in short-term and long-term effects of handheld use in the classroom.

7.2. Moderator analyses

None of the considered moderators had a significant impact on the effect of handheld use and academic achievement. However, it is doubtful whether these findings reflect the actual influence of the examined moderators because with a few exceptions, the cell counts were too small for conducting moderator analyses. Although other meta-analyses have identified significant moderators in the field of mobile learning (e.g., [68,72,84]), there were no consistent findings between these various meta-analyses, which is presumably due to the very different inclusion criteria for primary studies. Because the meta-analysis presented here is specifically tailored to the effects of handhelds in formal educational settings and imposes very strict requirements on the methodological quality of its included primary studies, it is likely that the findings differ from those of other meta-analyses. However, despite the small number of studies resulting from these rigorous methodological quality exclusion criteria, the findings and interpretations of the included studies here are very meaningful and it may be possible that the described relationship between handheld use and academic achievement is indeed relatively generalizable across different contexts, persons, and conditions. More well-designed primary studies are needed to further test this assumption.

7.3. Influence of learning designs

The learning design used in the respective treatment and control groups was analyzed both as a moderator variable and as an independent variable. Our results showed that the use of handhelds has medium to high effects on academic achievement across all learning designs. As an example for the learning design "self-directed learning", Erbas and Demirer investigated the effects of augmented reality (AR) activities on students' academic achievement and motivation in a biology course. The control group followed the regular biology course program, whereas the experimental group students conducted AR activities in addition to the course program using tablets. Motivation of the students in the experimental group increased more than that of the students in the control group while no significant difference was found for academic achievement scores. With respect to the learning design "inquiry-oriented learning", Huizenga et al. compared two groups of students in acquiring historical knowledge of medieval Amsterdam. Results showed those pupils who played the game to be engaged and to gain significantly more knowledge about medieval Amsterdam than those pupils who received regular project-based instruction.

The two examples illustrate the high subject and situation specificity of many applications of handhelds in formal educational settings. Since the underlying learning design often results from the technical specifications and vice versa, it does not seem possible to vary the overarching teaching style while maintaining the same technical tool in many of the studies analyzed here. Stated differently, few studies to date have considered the use of handhelds on a higher level across different subjects and/or teaching units making it difficult to draw meaningful conclusions for educational practice. In conjunction with the rather limited amount of studies, this means that overall there are not enough studies that allow a valid conclusion on the relevance of certain learning designs in the context of handheld use. Another fundamental problem is that there are hardly any studies available that test different adaptive learning designs against each other, e.g. AR activities in direct instruction vs. self-regulated learning. As long as such studies are not available in a critical quantity, all practical conclusions about how to implement handhelds into classes remain tentative.

Our pattern of findings regarding learning designs differs from that of Sung et al. [68], who, for instance, reported significantly lower effect sizes for lectures ($g = .39$) and cooperative learning ($g = .26$). Yet, Sung and colleagues looked at a broader pool of primary studies by examining mobile devices in general without the more narrow focus on handhelds chosen here. However, the clear focus on a specific mobile device and the aforementioned high-quality standard for primary studies with meaningful study designs strengthen our conclusion that the effect sizes determined are highly valid and credible.

In line with Sung et al. [68], inquiry-oriented learning designs had the (descriptively) highest effect size on academic achievement. Conceptually, various authors emphasize the potential fit of the inquiry-oriented learning concepts and the multiple action options that handhelds offer to the individual learner (e.g., [43,64]). As Onyema et al. [54] put it, "[…] *mobile devices often come with fascinating features, apps and functions that motivate learners to connect to the internet, think critically, and to actively engage in authentic and creative learning inquiries, collaborations and discussions*." The second highest effect size was found for the mixed learning design, in which teachers use several teaching methods at the same time. Although the combinations were very heterogeneous across the studies, it can be generally stated that lesson planning adapted by the teacher to handheld use does not seem to be disadvantageous. This is consistent with Hattie's [32] findings that effective teaching can be achieved in many ways. An interesting question for future studies is to investigate whether inquiry-oriented and mixed learning designs have similar positive effects on learning-related factors beyond academic achievement as examined in this meta-analysis.

7.4. *Utility of findings and practical implications*

Despite the ubiquitous availability of handhelds and digital learning scenarios, challenges and barriers still remain for teachers when integrating mobile devices and technologies into teaching (Dias & Victor, 2014). The reasons for this are manifold, ranging from teachers' own educational background (e.g., regarding the extent of digital competencies taught in university programs) to technical (e.g., connectivity, maintenance), personal teacher-related (e.g., reservations about usefulness and applicability, stubborn adherence to familiar teaching methods) or external (e.g., high equipment costs, lack of policy and government support) aspects [50,74]. On the other hand, even today, many topics can be taught with both analog and digital materials, as well as in hybrid form - so far, teachers are often free to decide which method they prefer to reach their teaching aims. However, in order to make informed didactical decisions in favor or against handheld use, understanding and knowledge of the effects of these methods are necessary. The relatively homogeneous pattern of results and broad empirical evidence presented here, according to which handhelds can be useful not only for academic performance but also for many other learning-related outcomes, enables us to derive a number of practical implications. First, teachers and other school professionals are encouraged to implement handhelds in their formal classroom work not only to enhance student achievement, but also short-term outcomes as motivation to learn, positive attitudes toward and satisfaction with learning, and to facilitate cognitive aspects of learning by reducing cognitive load. Second, since student characteristics like age and gender were not revealed as moderating factors, teachers can be confident that the implementation of handhelds is appropriate regardless of grade level and gender. Third, as the type of device did not enhance or diminish the observed effects, teachers may feel free to choose the handheld they prefer in light of their pedagogical concept. While smartphones tend to allow for more dynamic and mobile use (e.g., in excursions), tablets could sometimes be the better choice in cases where a larger display is advantageous (e.g., in music classes;). Fourth, although inquiry-oriented learning seems to be particularly beneficial for enhancing learning-related outcomes and achievement, the use of handhelds will also have positive effects in the context of other learning designs. Teachers can therefore feel encouraged to try out new pedagogies aligned with the special features of mobile technologies based on their individually preferred teaching style.

7.5. *Limitations and suggestions for further research*

The present meta-analysis has some limitations. First, due to our strict inclusion and exclusion criteria, only a small number of studies was included in the analysis which may have resulted in biased estimations of main effects. Yet, an even greater threat for the validity of our findings refers to the small number of moderator variables we could implement into the meta-analysis. Given the described high heterogeneity of studies on the use of handhelds in educational settings, more and qualitatively broader studies on the effectiveness of handheld use and possible moderators are clearly needed (see [68], for a similar problem). Additionally, many learning-related outcomes of the present analysis (such as intrinsic motivation and self-efficacy) are well-known positive predictors of achievement (e.g. [62,66]). However, this causal explanation for higher achievement through handheld use via these learning-relevant variables was not examined in our meta-analysis due to a lack of primary studies examining this mediation. Future research should therefore examine the indirect effect of handheld use on achievement via the enhancement of motivational variables taking into account the above mentioned temporal dynamics of short and long-term effects. Here, too, contextual differences in handheld use should be considered as moderating factors of the effects. Finally, the present meta-analysis sought to close a gap in our knowledge regarding the mechanisms of learning with handhelds, which consequences it has for learning, and where, how, and for whom the use of handhelds in learning institutions is the most effective and beneficial [47]. A critical issue for further systematic research could be to examine the specific use of handhelds in more detail, such as teaching methods, didactical concepts, activities on handhelds and their duration, and software use. In the long-term, this could help to explore the potential benefits of utilizing handheld devices and promote the sensible and effective use of handhelds in education. Beyond that, we recommend organizing exchanges of ideas between researchers and practitioners to promote the evidence-based use of handhelds in educational institutions. The results provided here may contribute significantly to this discussion and may also help to build an overarching theoretical framework on the impact of handheld use in the classroom.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Further reading

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