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META-ANALYSIS

Usability of Mobile Applications: A Consolidated Model

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ABSTRACT Mobile devices have become an integral part of the digital ecosystem, connecting people, businesses, and information around the world in ways never before possible. In particular, smartphones, tablets and other handheld devices equipped with mobile applications have changed every aspect of our lives. Today, a user can choose from nearly five million applications available for both Android and iOS operating systems. However, only 0.5 percent of applications succeed in the marketplace. Many factors contribute to their failure, including poor design, lack of value, privacy violations, and usability issues. While usability is often identified as a major concern, there seems to be no agreement between researchers and practitioners on its nature, although many models have been developed. This paper attempts to find a consensus by synthesizing the state of the art literature. More specifically, we aim to develop a consolidated, universal usability model for mobile applications, through the lens of existing human computer interaction theory. In order to achieve this goal, our study uses a mix of qualitative and quantitative methods. Overall, the research methodology consisted of two steps. First, we conducted a systematic literature review to identify, collect, and analyze current research on mobile usability. Second, we used the meta-analysis approach to quantitatively describe the extracted data and summarize the findings. The PACMAD+3 model was developed and discussed in light of the results obtained and the PACMAD model. While our model borrows seven attributes from its ancestor, the remaining three attributes were derived from the synthesis of other studies, along with three external factors adopted from the ISO 9241-11 standard. In addition, we reviewed existing definitions of usability attributes. We expect that this unified approach will lead to a better understanding of mobile usability, including all relevant attributes and factors, thus making a significant contribution to theory. On the other hand, in practice, the PACMAD+3 model can be used to translate abstract attributes into tangible terms, which is particularly useful in empirical research focused on measuring and evaluating the usability of mobile applications.

INDEX TERMS Model, usability, mobile application, meta-analysis, review.

I. INTRODUCTION

A mobile application (mobile app, or simply app) is software designed and developed specifically for use on a mobile (wireless) device, such as a smartphone or tablet. Due to the portability of mobile devices, onboard mobile apps have definitely changed our lifestyles [1] and allow companies to stay connected with their customers in real time [2]. With 6.3 billion smartphone users worldwide [3], it's no surprise that this industry is thriving. There are approximately 1.96 million apps available for download in the Apple App Store and 2.87 million apps available in the Google Play Store [4].

Despite the ubiquity of smartphones, approximately 99.5 percent of apps simply fail [5]. Obviously, getting initial downloads of an individual app comes with its own set of challenges. Specifically, statistics show that 25 percent of users abandon an app after one use [6], while almost one in every two apps is uninstalled within 30 days of being installed [7]. At this point, the question naturally arises: why do some applications fail while others succeed? Obviously, there is no one-size-fits-all answer to this question, but there are some common factors that are known to contribute.

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Since the majority of applications that offer nothing useful or unique tend to be the ones that are uninstalled the most [8], the most interesting part is the remaining part which concerns those initially accepted but eventually rejected. Reported reasons include issues related to intrusive ads, privacy, as well as poor onboarding experience [9]. In fact, by giving mobile application users the power to speak for themselves, one can discover that usability, covering a variety of malfunctions and issues, is among major their concerns [10], [11], [12].

The study of mobile application usability has become a focal point for the human-computer interaction research community, driven by the escalating global use of mobile devices [13], [14], [15], [16], [17]. The development of applications is a challenging task due to the different purposes of each application and the different needs and expectations of individual users. Given the variety of applications designed for each specific purpose, the success of an application depends, among other factors, on its usability [18], [19], [20], [21], [22].

Although there are many mobile usability models and systematic reviews, there seems to be no agreement among researchers. Therefore, this study attempts to find a consensus by synthesizing the state of the art literature. In other words, our goal is to develop a consolidated usability model for mobile applications through the lens of a combination of qualitative review and meta-analysis.

The rest of the paper is organized as follows. In Section III, we discuss the research background. In Section III we present the methodology applied. In Section IV we analyze the results obtained. In Section V we introduce the PACMAD+3 model. In Section VI we discuss the model in more detail, as well as the contributions and limitations of the study. In Section VII we conclude the study.

II. BACKGROUND

In light of the results reported by [23], the most commonly adopted usability definition for mobile applications is ISO 9241-11, which is also considered valid in the current study. Hence, usability is understood as the "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [24].

Since usability as such does not exist, the standard also outlines two factors: user and goal. The former refers to a person who interacts with a system, product or service, while the latter specifies a set of activities undertaken to achieve a specific goal. In other words, usability is materialized by a user interacting with an application while performing a task.

In order to measure and further evaluate usability, the above standard specifies three attributes, namely:

- effectiveness: "the accuracy and completeness with which users achieve specified goals";
- efficiency: "the resources expended in relation to the accuracy and completeness with which users achieve goals";
- satisfaction: "the comfort and acceptability of the work system to its users and other people affected by its use".

Last but not least, the "context of use" is defined as the "characteristics of users, tasks, and organizational and physical environments" [24]. It is a critical concept in human-centered design and mobile usability studies. It refers to the specific environment, conditions, and characteristics in which a product, system, or interface is used. Understanding the context of use is essential for usability design and evaluation to be relevant and actionable.

It should be noted that there are many related terms included in the above standard that are beyond the scope of this study.

A. RETHINKING USABILITY

For usability practitioners, the term "usability" as a goal is equivalent to quality of use [25], which means that the product is used by real and satisfied users. Therefore, usability has two equivalent roles in development: as an imperative, as one of the highest design goals [26], and as a general quality measure of the interaction between a user and an application [27].

Since the introduction of the first smartphone, usability for mobile applications seems to have taken on a new meaning due to certain physical limitations of mobile devices. Firstly, the size of a touch screen is one of the most influential factors on user performance [28], while at the same time being a standard input and output device. Secondly, the battery life of mobile devices is another constraint, as "power hungry" applications can quickly drain a device's battery [29]. Despite recent advances in battery technology, it remains one of the biggest obstacles to the further development of mobile devices [30]. Thirdly, mobile devices have limited processing power and storage capacity compared to desktop equivalents [31]. This can affect the speed and performance of complex tasks or resource-intensive applications.

From the perspective of software vendors, the mobility paradigm introduces a different environment for applications, requiring significant changes in their design and development [32], [33]. Mobile app developers need to consider the differences in screen sizes as more users are using different mobile devices, including smartphones, tablets or other portable devices [34]. In addition, a responsive design for a smartphone may be different from one for a tablet due to the different screen sizes and resolutions. Last but not least, misunderstanding user expectations and neglecting usability requirements is actually one of the most common challenges software companies face during their mobile application development process [35], [36], [37], [38], [39].

Therefore, usability in the context of mobile applications needs to be reconsidered in the light of limited resources on the one hand and different user requirements on the other, taking into account the current body of knowledge as well as emerging trends in ongoing research and development.

III. METHODOLOGY

By design, our study is a mix of qualitative and quantitative in nature. In the case of the former, we used a systematic literature review method to identify, collect, and analyze the current body of research devoted to mobile usability. In the case of the latter, we used meta-analysis, a relatively new technique in usability research, to quantitatively describe the data and summarize the findings.

A. DATA EXTRACTION

We followed a systematic approach to collect, classify, and analyze the current body of knowledge on mobile application usability. First, we defined a review protocol to reduce the possibility of bias in the selection and analysis of studies [40]. The elaborated protocol is based on a previously established format [41] and consists of seven parts, which are discussed individually below.

1) RESEARCH QUESTIONS

Considering the goal of the study, the following two research questions were formulated:

RQ1 What usability models exist for mobile applications?

RQ2 Are there systematic literature reviews on the usability of mobile applications?

RQ3 What usability attributes are identified in systematic literature reviews of mobile applications or used to construct usability models?

It should be noted that in order to collect as many publications as possible, it is necessary to formulate research questions that can cover the entire scope of this study. Therefore, two questions were formulated because different research methods could be used and included in the metadata of the paper.

2) SEARCH QUERY

The search query was defined by the presence of *usability* and *mobile*, with the AND operator between them, in titles, abstracts and keywords. These unique keywords, combined in this order and in this amount of metadata, broadly embody the research topic and the adopted context to the current studies. On the other hand, we tried to keep the scope of the keywords narrow, because if the scope is not properly defined, the search engine may return a lot of studies that are not necessarily in the valid scope. Note that some initial informal searches were done to determine the best keyword combination.

3) DATA SOURCE

We used the online Scopus database, available at http://scopus.com, since it provides comprehensive coverage of peer-reviewed books, journals, conference proceedings across many disciplines and various forms of writing [42], both academic and non-academic [43], in total covering more than 49 million records [44]. In addition, all data elements in Scopus are continuously monitored and improved through extensive quality assurance processes.

4) INCLUSION CRITERIA

Explicit inclusion criteria were established to identify a subset of high quality papers from the results of the various databases. The use of quality research to answer the research questions ensures a certain level of validity of the results. Five inclusion criteria were based on recognized approaches to conducting SLRs [45], [46].

The adopted inclusion criteria (IC) were:

IC1 Paper is written in English.

IC2 Full text is available.

IC3 Paper is not a duplicate publication already considered.

IC4 Paper is not a demo paper.

IC5 Paper is classified to the subject area: Computer Science, Engineering, Social Sciences, Decision Sciences, Multidisciplinary.

The above inclusion criteria were applied as a first filter to the results returned by the Scopus database.

5) EXCLUSION CRITERIA

Consequently, the following exclusion criteria (EC) were defined, which supplement the first filter settings:

EC1 The paper is written in a language other than English.

EC2 The full text of the study is not available.

EC3 The study is a book or book chapter.

EC4 The study is a letter or short survey.

EC5 The study is an erratum, note, or editorial.

EC6 The study has been retracted.

The above exclusion criteria were applied as a second filter to the results returned by the Scopus database.

6) SEARCH EXECUTION

In the first run, the online Scopus database returned 14,226 documents for the query. In the second run, the inclusion criteria were applied to this set, which returned 11,252 documents. Finally, in the third run, the exclusion criteria were applied, which returned a set of 10,629 documents. Interestingly, the first five papers were published in 1995, while the remaining 8812 (83%) have been published since 2010, with the the highest peak of 847 (8%) in 2019.

7) DATA VOLUME

The extracted volume of 10,628 documents involved four different categories, namely: conference paper (6,450), article (3,481), conference review (526), and review (172).

B. DATA ANALYSIS

Second, the review process consisted of four five parts, including:

1) Search for the article by its title using one of the keywords model, review, systematic.
2) Application of the selection criteria.
3) Quality screening and evaluation.
4) Add the positively evaluated article to the list for data synthesis.

5) Find and individually evaluate the set of attributes used to build a usability model or discussed in a conducted review.
6) Add positively evaluated attributes to the list for a new model development.

In the first step, the titles of the papers were screened by performing three separate searches. Each time one of the following keywords was: *model*, *review*, or *systematic*. The number of results obtained was 448, 224, and 113 respectively.

Next, each title was carefully investigated by evaluating its declared objective, scope or application, or research method used, or targeted audience. In this sense, the following selection criteria (SC) were used:

SC1 A usability model is generic in nature.
SC2 A usability model is not context specific.
SC3 A usability model is not intended to evaluate the usability of a single application or a particular type.
SC4 A review, as a noun, is used to specify the research method.
SC5 A systematic is used as an adjective to specify the research method.
SC6 No specific target audience is indicated.

Next, if the paper met the selection criteria, then it was subjected to a quality review using the following seven quality criteria (QC):

QC1 [Topic Appropriateness]: Is the paper related to the usability of mobile applications?
QC2 [Research Objectives]: Are the goals of the research clearly stated?
QC3 [Methodology]: Is the research methodology used in the study appropriate and valid?
QC4 [Presence of Usability Model]: Is the developed or presented usability model for mobile applications the primary focus of the research?
QC5 [SLR Reliability and Generalizability] Did the reported systematic literature review follow an accepted guideline or adopted an established SLR framework?
QC6 [Usability Attribute Internal Validity] Is the identified, extracted, elaborated usability attribute internally valid?
QC7 [Results Conclusiveness] Are there any conclusive results or findings possible to use to compare with other studies?

In the fourth step, from the total number of 785 papers screened by title, eight papers met the above quality criteria and were finally positively classified as valid for further analysis and synthesis. It should be noted that in our study, synthesis involves "building a picture of the whole" from studies of its parts [47]. In other words, this approach was used to review qualitative studies and identify different attributes of mobile usability that can be brought together in a new model. The list of these studies is presented in Table 1.

To determine the most influential publications in the field, articles were sorted in descending order by the average number of citations per year, calculated by dividing the total number of citations by the number of years since publication. In addition, each study has been assigned a unique code, where *M* stands for a model and *R* for a review. We believe that such a simple measure informs the reader of the nature of the research in an easy and accessible way.

As one can notice, the work of [48] has the highest impact (26.59), among all other studies, also collected the highest number of citations (452). The second place belongs to the study of [23] (25.67), followed by [49] (11.20).

Now, considering two last quality criteria, namely QC6 and QC7, all individually extracted attributes were carefully examined, and approved, in case of meeting the requirements, otherwise disapproved. The following terms, called "attributes," were rejected because they actually refer to:

- guidelines such as aesthetic design, flexible input;
- heuristics such as visibility of system status, matching between system and real world;
- mobile app features such as cancel support, undo support, personalization;
- obscure notions such as explicit action, predictability, information density, brevity, navigability, message quality, balance, function integration, content provision, navigation and control, error management, system support, user error prevention, training, learning performance, interaction, Navigation, attitude, Feedback
- user interface characteristics such as prompting, legibility, font style uniformity, color uniformity, screen readability,
- sub-attributes such as: accuracy,

Furthermore, the attributes mentioned by only one study were not taken into account, namely: Adaptability, Acceptability, Comprehensibility, Intuitiveness, Safety, Privacy, Productivity, Universality, Trustfulness

The list of positively classified attributes is presented in Table 2. Attributes were sorted in descending order by the number of occurrences, given in the last column (marked with #). In addition, Table 3 shows their distribution over time.

IV. FINDINGS

Based on the extracted data already briefly discussed, now we address the research questions in more detail.

[RQ1] What usability models exist for mobile applications? To this day, four usability models have been introduced, developed and reported by three different research teams.

The first model (M01), called Quality in Use Integrated Measurement (QUIM), was developed by Seffah et al. [48]. As a rationale, the authors highlighted the limitations and complementarities of the various standards that existed in the contemporary literature, ultimately unifying the existing models into a single consolidated, hierarchical usability model. The QUIM model consists of 10 unique attributes. In addition, two other potential attributes were suggested for consideration in future versions of QUIM, namely portability and adaptability. While the former refers to the ability of a system to be displayed on different platforms, the latter refers to the ability of a system to be adapted or to adapt itself

TABLE 1. The list of positively classified studies (retrieved from the Scopus database on November 3, 2023).

Code	Authors &Year	Title	Impact
M01	Seffah *et al.* (2006) [48]	Usability measurement and metrics: A consolidated model	26.59
R01	Weichbroth (2020) [23]	Usability of mobile applications: A systematic literature study	25.67
M02	Baharuddin *et al.* (2013) [49]	Usability Dimensions for Mobile Applications-A Review	11.20
R02	Alturki and Gay (2019) [50]	Usability Attributes for Mobile Applications: A Systematic Review	4.25
M03	Fabil *et al.* (2015) [51]	Extension of Pacmad Model for Usability Evaluation Metrics Using Goal Question Metrics (GQM) Approach	3.63
R03	Coursaris and Kim (2006) [52]	A Qualitative Review of Empirical Mobile Usability Studies	1.94
M04	Ammar (2019) [53]	A Usability Model for Mobile Applications Generated with a Model-Driven Approach	1.50
R04	Huang and Benyoucef (2023) [54]	A systematic literature review of mobile application usability: addressing the design perspective	0

TABLE 2. The list of positively classified usability attributes for mobile applications.

Item	Attribute / Code	M01	R01	M02	R02	M03	R03	M04	R04	#
A1	Learnability	√	√	√	√	√	√	√	√	8
A2	Efficiency	√	√	√	√	√	√		√	7
A3	Effectiveness	√	√	√	√	√	√		√	7
A4	Satisfaction	√	√	√	√	√	√		√	7
A5	Usefulness	√	√	√	√				√	5
A6	Memorability		√			√	√		√	4
A7	Errors		√		√	√	√			4
A8	Simplicity		√	√	√				√	4
A9	Attractiveness		√	√	√			√		4
A10	Accessibility	√	√				√			3
A11	Operability		√				√	√		3
A12	Consistency		√					√	√	3
A13	Cognitive Load		√			√			√	3
A14	Aesthetic		√	√						2
A15	Understandable			√	√					2
A16	Easy of Use		√						√	2
A17	Understandability		√					√		2

TABLE 3. Distribution of mobile application usability attributes over time.

Attribute / Year	2006	2006	2013	2015	2019	2019	2020	2023	#
Learnability	•	•	•	•	•	•	•	•	8
Efficiency	•	•	•	•	•		•	•	7
Effectiveness	•	•	•	•	•		•	•	7
Satisfaction	•	•	•	•	•		•	•	7
Usefulness	•		•		•		•	•	5
Accessibility	•	•					•		3
Memorability		•		•			•	•	4
Errors		•		•	•		•		4
Operability		•				•	•		3
Simplicity			•		•		•	•	4
Attractiveness			•		•	•	•		4
Aesthetic			•				•		2
Understandable			•		•				2
Consistency						•	•	•	3
Cognitive Load				•			•	•	3
Understandability						•	•	•	3
Easy of Use						•	•		2

to context and understanding. Besides, both 26 measurable criteria and the corresponding 127 specific usability metrics were introduced and discussed in detail. A consolidated QUIM can also be seen as a theoretical framework, as it provides consistent definitions of usability attributes, criteria and metrics, and shows the hierarchical relationships between them. From a practical perspective, it is also intended to serve as a guide for planning usability measurement.

The second model (M02) [49] was developed based on the review of empirical studies devoted to the usability of mobile applications. According to the authors, the model is intended to provide a practical guideline that could assist researchers and practitioners in designing and measuring the usability of mobile applications. While a total of 18 usability attributes were identified, only 10 of them were included in the model. In addition, 4 contextual factors were distinguished, related to the user, the environment, the technology, and the task or activity. The model contributes to both theory and practice, as it can be used to operationalize specific measurements used in usability testing studies, as well as to determine which usability dimensions should be considered when designing and measuring usability levels for mobile applications.

The third usability model (M03), introduced by Fabil et al. [51], is an extension of the PACMAD model [55], consisting of 7 attributes. The development of this model was motivated by the lack of low level metrics representing each usability attribute. The study was carried out in four phases. Phase one involved a comprehensive literature review to collect relevant studies. Phase two aimed to extract usability evaluation metrics. Phase three used the Goal-Question-Metric (GQM) approach [56] to develop an extension of the PACMAD model. Phase four was the empirical evaluation, through two experiments to test the usability metrics of applications in two different mobile applications. In this way, the validity, effectiveness and reliability were empirically confirmed.

The fourth usability model (M04) [53] was adopted from the study by Ammar et al. [57], which extended the ISO/IEC 9126 standard [58]. According to the author, the rationale is to address some of the shortcomings of existing usability models when applied to mobile applications. Specifically, it focuses on two characteristics: small screen size and data entry methods. The model consists of four sub-characteristics Learnability, Understandability, Operability and Attractiveness, which are broken down into tree, five, four and four usability attributes. It should be emphasised that the model is of practical relevance and is a source of many valuable guidelines and tips.

[RQ2] Are there systematic literature reviews on the usability of mobile applications? The current literature provides four reviews that have been conducted in a systematic, reproducible and transparent manner.

The first review (R01), presented by Weichbroth [23], posed three research questions strictly related to usability of mobile applications, in particular definition, attributes, measures and evaluation methods. To answer these questions, a volume of 790 documents covering the period from 2001 to 2018 was analyzed. In terms of usability attributes, a set of 75 usability attributes was identified. However, the majority (51) were referenced only once, as the research objective was to evaluate a specific feature, property, or user perception of a selected mobile application. The remaining (24), referenced twice or more, shows a broad perspective on inherent qualities, so far adopted and adapted to study mobile applications usability.

The second review (R02), written by Alturki and Gay [50]. This study delves into existing usability models, frameworks, and guidelines that were recognized from 18 papers. By synthesizing this body of research, the authors identified 9 usability attributes. There are several other interesting findings. The early studies were conducted in a laboratory setting, while the later studies were held in the field, meaning that the testing of applications takes place under real-world conditions. Researchers then focused on usability testing of various applications. Next, the shift from laboratory to field settings has fostered the development of new attributes that were later evaluated in the case of practical applications. The emerging attributes are related to the ease of use in the extent of performing multiple tasks, intuitiveness, security and application power consumption.

The third review (R03), conducted by Coursaris and Kim [52], recognized 9 usability attributes. The findings from the comparison of general usability and mobile usability studies provide researchers with guidance for future research directions. On the other hand, the research offers practitioners insights into the aspects of technology that should be factored into a usability evaluation of mobile applications. It is also worth mentioning that the authors developed the usability framework, which could actually be considered as a cause-and-effect model. The left side includes usability attributes surrounded by four factors (user, environment, technology, and task), while the right side points to five consequences of (high) usability, including: adoption, retention, loyalty, trust, and overall satisfaction. Since such a framework undeniably contributes to the theory of human-computer interaction, it can be adopted to develop and test hypotheses regarding their statistical significance for numerous different mobile applications or mobile services.

The fourth review (R04), presented by Huang and Benyoucef [54], identified 22 attributes, but 14 were positively classified. In our opinion, the authors have taken a broad view of usability, going beyond the commonly accepted theoretical boundaries. However, such an understanding does not diminish the high value of the content of the study. Moreover, this comprehensive discussion also acknowledges that usability is an important requirement in the development of mobile applications, informing about the optimal approaches, considering both the design and development tasks.

[RQ3] What usability attributes are identified in systematic literature reviews of mobile applications or used to construct usability models? It is easy to see that a total of 17 usability attributes have been identified. Unexpectedly, Learnability is covered by all the studies analyzed. On the other hand, it is not surprising that the next three attributes are Efficiency, Effectiveness and Satisfaction, since the ISO 9241-11 standard has usually set theoretical boundaries. The next attribute that contributes to mobile usability is Usefulness. Four attributes occurred four times, namely: Memorability, Errors, Simplicity, and Attractiveness. Furthermore, there are 4 attributes (Accessibility, Operability, Consistency, and Cognitive Load) that are mentioned by three studies. The remaining 4 attributes, including Aesthetic, Understandable, Easy of Use, and Understandability, are referenced by only two studies.

V. MODEL DEVELOPMENT

Given the input (Table 2), the bottom-up approach has been adopted [59]. In particular, the process involves synthesizing individual attributes that are closely related with the ultimate goal of building up to a unified model. In this line of thinking, further data analysis and synthesis begins with the attributes in ascending order by number of occurrences. More specifically, data synthesis involves consolidating the results of primary studies and, when feasible or appropriate, applying various forms of quantitative and qualitative analysis [60].

First, existing definitions of individual attributes were compared in pairs when their meanings were found to be more or less similar. Second, attributes were grouped into broader categories based on commonalities and internal relationships. These categories are inherently more abstract, representing higher-level concepts that emerge from the coded data. Alternatively, if an individual attribute was found to be part of a previously unidentified mobile usability model, that model was also carefully examined.

A. DATA SYNTHESIS AND GROUPING

1) UNDERSTANDABILITY

a: UNDERSTANDABILITY (A17) AND UNDERSTANDABLE (A15)

Understandability was not defined by Weichbroth [23], but was articulated by Ammar [53] as "the ability of the software system to allow users to understand its application and to easily performs tasks". The other related attribute is Understandable, which is not defined by either Baharuddin et al. [49] or Alturki and Gay [50]. Considering both the specific and general understanding of these terms, along with usability theory, we opt to merge the latter with the former to form a single entity (A19), and eventually include it in our model.

Furthermore, by confirming the validity of understandability as a relevant usability attribute, we define it as the ability of an application to enable a user to understand whether and how it is suitable for particular tasks and conditions of use.

2) EASE OF USE

a: EASE OF USE (A16) AND LEARNABILITY (A1)

According to Weichbroth [23], ease of use has been pointed out as a synonym for learnability. More specifically, learnability is defined as the degree of ease with which a user can interact with a newly encountered mobile application without getting guidance or referring to documentation. In a broader sense, the attribute meaning is associated with the user's ability to learn his application [53]. In other words, learnability refers to how easily and effectively a user can acquire the knowledge or skills, whereas ease of use is a separate concept, closely related to a user friendly design. The relationship between the two can vary depending on the context, the prior knowledge or experience of the individual, and the design of the user interface (UI). Therefore, we do not advocate combining these two attributes.

b: EASE OF USE (A16) AND UNDERSTANDABILITY (A17)

In general, there is a strong relationship between understandability and ease of use. When a mobile application is easy to understand, it often contributes to ease of use. Specifically, understanding how an application works, the steps involved, and the overall logic behind its operation can improve usability by reducing the learning curve. However, it's important to note that understandability alone does not guarantee ease of use. Other factors, such as the UI design, the clarity of instructions, also play crucial roles. While an app may be understandable in theory but still be difficult to use if the interface is poorly designed or if the instructions are unclear. Thus, we are not in favor of merging Ease of Use with Understandability.

Obviously, users are more likely to be satisfied with an application that is intuitive, requires minimal effort to navigate, and meets their needs efficiently. In a broader sense, ease of use is a critical factor that influences users' perceptions, attitudes, and intentions to adopt and use a particular mobile technology. That said, we are in favor of including this attribute in our model. For the sake of clarity, we understand ease of use as the degree to which a user perceives that using a mobile application is free of unnecessary effort.

3) USER INTERFACE DESIGN ATTRIBUTES

During the analysis of the remaining usability attributes, it has been spotted a group of attributes, sharing and exhibiting similar nature, which corresponds to the design of user interface. These attributes are:

- **Aesthetic (A14)**. While [23] does not define Aesthetic, for [49] it is identified with beauty and classical expressiveness.
- **Consistency (A12)**. While neither [23] nor [53] do not define Consistency, for [54] consistency is to "maintain consistent design features".
- **Attractiveness (A9)**. Only [53] define Attractiveness as "the capability of the software system to be attractive to the user".
- **Simplicity (A8)**. Reference [23] defines simplicity twofold. First, as the "degree of being easy to understand". Therefore, this notion can be also termed as "understandability". Second, simplicity means "being uncomplicated in form or design". Thus, simplicity is perceived as a specific feature of the user interface. Considering the latter view, it is also acknowledged by [49] who argue that "minimalist design means dialogs that contains non irrelevant information, which also entails simplicity". Similarly, [54] argue to ensure simplicity in mobile app design and features. However, in a broader view, for [49] simplicity "comprises three dimensions: aesthetics, information architecture and task complexity".

While we do not deny the importance of the above mentioned attributes, we claim that they are not strictly related to usability. Thus, we are in favor of excluding this group from further analysis.

4) COGNITIVE LOAD

Cognitive Load (A13) was introduced by Harrison et al. [55] as the main contribution of the PACMAD model, along with the other usability attributes well known at the time, including: Errors (A7), Memorability (A6), Satisfaction (A4), Effectiveness (A3), Efficiency (A2), and Learnability (A1). This group of attributes is further discussed in the next section, taking into account the influence and recognition of the PACMAD model in the global research stream on mobile usability.

5) OPERABILITY

While neither Weichbroth [23] nor Coursaris and Kim [52] do not define Operability (A11), for Ammar [53] it is the "capability of the software system to allow users to operate and control it". There are at least three premises in favor of considering operability as a mobile usability attribute. Firstly, mobile devices by their very nature impose physical limitations that affect certain user capabilities. Secondly, the term "mobile" in this context refers to the mobility of the devices themselves, i.e. mobile applications are specifically designed and optimized for use on smartphones and tablets. In other words, any mobile application is designed to be used away from a fixed location. In this line of thinking, thirdly, operability reflects its ability to adapt and be used in different circumstances by a user.

That being said, operability also corresponds to the context sensitivity which is understood as the degree to which a mobile application adapts to the environment. As an example, let's consider the following situation. A user (driver) is using a mobile navigation application. While driving during the day, the road passes through a tunnel with different lighting characteristics, which disrupts the user's ability to both perceive the displayed information and use the application. In this case, operability is demonstrated by the application's ability to automatically change the color mode and switch back to the previous settings when appropriate. Obviously, there are many other examples where the contextual sensitivity is important to maintain an effective and user-friendly interaction. To sum up, we define operability as the ability of the mobile application to allow the user to operate and control it in different contexts of use.

Since the existing literature provides evidence that operability contributes to usability of mobile applications, we tend to include this attribute in our model as well.

6) ACCESSIBILITY

For Seffah et al. [48] Accessibility (A10) is the ability of a software product to be used by users with some form of disability and by older people [61]. The other two studies did not define this attribute. In addition, if we look at the list of accessibility guidelines for mobile phones, there are several references to users with disabilities [62]. Since our goal is to develop a generic usability model, Accessibility is out of scope and will not be considered anymore.

7) USEFULNESS

Usefulness (A5) was considered in two studies in the following way:

- Seffah et al. [48]: whether a software product enables users to solve real problems; implies practical utility; depends on the features and functionality, reflects the knowledge and skill level of the users while performing some task.
- Huang and Benyoucef [54]: deliver users with useful information or services.

Considering the above, it can be understood that usefulness is a judgment about how relevant a particular mobile application is in providing information about a topic of interest to the user. On the other hand, usefulness is a judgment about the practical value of mobile application features. Obviously, these two terms do not correspond to usability theory.

Furthermore, while some authors equate functionality with usefulness [63], then others study usefulness and usability simultaneously but still conceptualize and evaluate them separately. Therefore, this attribute is excluded from the analysis.

B. PACMAD MODEL

While existing models typically include three attributes used to measure mobile usability, including effectiveness, efficiency, and satisfaction, others are often overlooked despite their likely impact on an application's success or failure in the marketplace. To fill this research gap, [55] introduced the PACMAD (People At the Centre of Mobile Application Development) model. The model consists of seven attributes that together reflect the usability of a mobile application. In addition to the three attributes mentioned above, the remaining four are: Learnability, Memorability, Errors and Cognitive Load.

It should be noted that its novelty lies in the conceptualization of cognitive load as an attribute of mobile usability. In their argumentation, the authors argue that unlike typical desktop software, users of mobile applications tend to engage in other activities, such as walking, while using their mobile devices. For example, a user may want to send a text message while walking, which may cause a reduction in walking speed as the user focuses on composing the message, thus diverting attention from the act of walking. For these reasons, it is important to consider how the use of a mobile device may affect the user's performance in these concurrent tasks.

To the best of our knowledge, the PACMAD model is the most widely accepted usability model for mobile applications. According to Google Scholar, the paper has collected 931 citations as of the end of November 2023, an average of more than 93 citations per year. This model has been appreciated by many independent researchers worldwide and makes a significant contribution to mobile usability studies by providing a solid theoretical foundation. It should be noted that this study is not indexed by the Scopus database and was therefore not identified by the systematic literature review presented and discussed in the previous sections.

Each of the PACMAD seven attributes has been reported to contribute to the overall usability of the application and therefore can be further used to evaluate its usability. Therefore, all seven attributes that constitute the PACMAD model are also included in our model. In addition, a detailed analysis of the literature, including recent research in the field of usability of mobile applications, and in particular the definition of each attribute, was compared and synthesized.

Below, we define all the usability attributes that constitute the PACMAD model, keeping the order in which they were originally discussed.

1) EFFECTIVENESS

Effectiveness refers to a user's ability to successfully complete a task within a defined context. It is typically assessed by measuring the participant's ability to complete a predetermined set of tasks.

2) EFFICIENCY

Efficiency refers to a user's ability to complete tasks quickly and accurately. This quality represents the user's productivity when using the mobile application. Several metrics can be used to measure efficiency, including the duration to complete a particular task or the number of keystrokes required to complete it.

3) SATISFACTION

Satisfaction refers to the perceived level of comfort and pleasure the user experiences while interacting with the mobile application. It is manifested in the user's attitudes toward the software and is usually subjectively assessed. Measuring user satisfaction often relies on tools such as questionnaires and other qualitative techniques that recognize individual differences among users.

4) LEARNABILITY

Learnability can be understood in two dimensions. First-time learnability assesses how easily a user can engage with a newly encountered system without external guidance or the need for documentation. This is measured by factors such as the number of attempts to complete a task, the assistance required to complete the task, and the occurrence of user errors. On the other hand, learnability over time refers to a user's ability to become proficient with an application. Typically, a user's performance is observed over a series of tasks to determine the time it takes to reach a predefined level of proficiency.

5) MEMORABILITY

Memorability refers to a user's ability to remember how to use an application effectively. Because software use can be inconsistent and sporadic, users need to retain the knowledge of how to use the software without having to relearn it after periods of inactivity. To measure memorability, participants can first be trained to use the software and then asked to perform similar tasks after a period of inactivity. Comparing the results from the two instances provides an assessment of the application's memorability.

6) ERRORS

From a user's perspective, errors encompass both the quantity and type of errors and other malfunctions that occur during the user's task performance. On the other hand, from the perspective of the quality of the mobile application in use, errors denote an application's ability to recover from such errors when they occur. The PACMAD usability model takes into account both the type of error and the frequency of its occurrence. Understanding the nature of these errors prevents their occurrence in future releases.

7) COGNITIVE LOAD

Cognitive load refers to the level of mental effort required from a user's working memory while using a mobile application. Cognitive load theory distinguishes three types of cognitive load: extraneous, intrinsic, and germane [23]. First, extraneous cognitive load refers to instructional and presentation schemas caused by mental activities and elements that do not directly support application use. Second, intrinsic cognitive load refers to task complexity caused by the number of elements in a task and the degree to which these elements are related to each other. Third, germane cognitive load refers to the amount of mental effort required to form schemas and actively integrate new information with prior knowledge during application use. In practice, instruments such as a subjective rating scale, a dual-task think aloud protocol, or eye tracking are commonly used to measure cognitive load.

C. PACMAD+3 MODEL

We extend the current version of the PACMAD model by adding three attributes, namely Understandability, Ease of Use and Operability. This results in an extended and consolidated usability model called PACMAD+3. Figure 1 shows the PACMAD+3 model and its relationships with the original PACMAD model and the ISO 9241-11 standard. In addition, three external factors are also identified, including: User, Task and Context of Use.

From the above, the first factor is a User (person) who interacts with a mobile application, and plays a central role [24]. A user can be described and profiled by collecting and using demographic data, including: age, gender, education, marital status, income, and employment. In addition, the user's prior experience is another important factor to consider for [55],

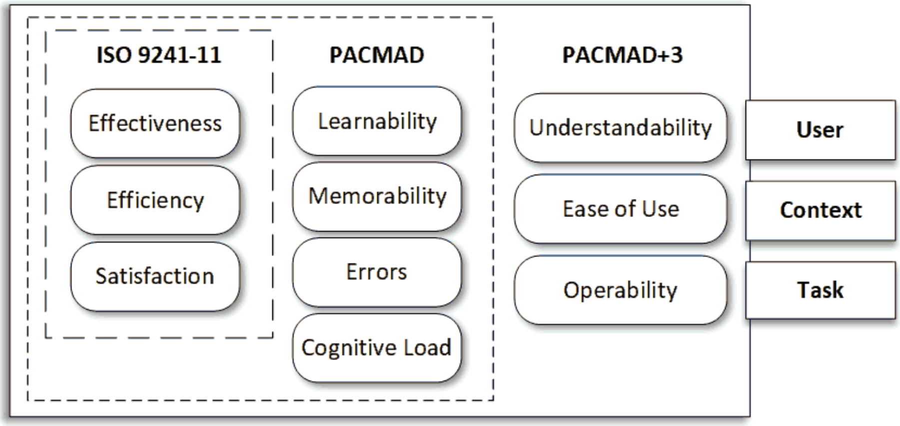

FIGURE 1. The PACMAD+3 model.

since the quality of interaction perceived by an experienced user and a novice user may be bipolar. On the other hand, from an evaluation perspective, the reported issues could be significantly different for various user profiles.

The second factor is the Task which refers to a set of activities undertaken to achieve a specific goal [24]. The design of the task plays a vital role in usability testing, which aims to discover issues by a user. The testing features should be structured in a unified tasks whose complexity designate the minimum number of users needed to obtain meaningful results.

The third factor is the Context of use. Here, context refers to the environment (physical location) in which the user uses the mobile application [55]. In a broader sense, this factor can be understood as the combination of users, goals and tasks, resources, and environment [24]. In usability studies, two types of consumed resources can be considered: reusable and expendable. The former refers to elements or components that can be used in different parts of the application or even in multiple applications such as address book, or photo gallery, while the latter refers to battery consumption, network usage, memory and CPU usage, to name a few.

VI. DISCUSSION

The results of the literature review show that mobile usability has been modeled in a similar way. It was found that the vast majority of existing models (including PACMAD) share four attributes, namely: Effectiveness, Efficiency, Satisfaction and Learnability. On the other hand, all four have been recognized for their importance by independent reviews.

It can be argued that these four attributes together form the cornerstone of a comprehensive framework that underpins mobile usability. The consistent recognition of these attributes across different models underscores their universal relevance. As mobile technologies continue to advance, it is expected that these fundamental principles will continue to guide both researchers and practitioners in the evaluation of mobile usability.

In theory, memorability refers to the user's ability to remember how to navigate and use the mobile application within a given time frame. Typically assessed by asking specific questions after a period of inactivity since the first interaction, memorability can be evaluated by comparing the user's responses between the first and last encounters. The results also show that many researchers do not consider memorability as an important part of usability. Reference [55] indicate that only 2 percent of studies considered memorability as an essential attribute, while interestingly [23] reported almost a quarter. In fact, memorability is often studied along with other usability attributes or different factors. For example, [64] found that learnability was correlated with memorability. [65] investigated how composition policies could affect the security, usability, and memorability of gesture passwords. In addition, studying gesture variability seems to be an interesting avenue of research, as a good balance between memorability and security must be found [66].

Another mobile usability attribute discussed by many researchers is Errors [64], [67], [68]. In general, it refers to problems that a user encounters while using mobile applications. The detection of such problems allows the development of preventive mechanisms to address specific user behavior. Moreover, this attribute serves as an indicator of how skillfully users navigate through mobile applications to achieve optimal task performance [69]. More specifically, error frequency is a commonly used metric in usability testing. Understanding the nature of the reported issues leads to an improvement in the mobile application's performance and accuracy, particularly useful for both designers [70] and developers [71]. On the other hand, Errors that occur negatively impact efficiency and user satisfaction [72].

Due to the size limitations of mobile devices and the multiple configurations of tasks to be performed, mobile applications are said to be particularly susceptible to the effects of cognitive overload [73]. Therefore, several studies have considered Cognitive load not only as an additional usability attribute, but as one of the primary attributes. For example, [74] considered the complexity of gesture interaction of older adults and the effect of cognitive load on the acceptability of different gestures. Reference [75] reported the ways in which mobile learning can benefit from the development of cognitive load aware systems that can detect and change the difficulty of the learning task based on the learner's cognitive state of the learner, benefiting to mobile usability as the app user moves between different environments and is thus exposed to different sources of cognitive load.

The quality model described in the ISO/IEC 25010 standard includes the eight quality characteristics, including usability, which is further subdivided into six subcharacteristics. One of them is Operability, defined as "the degree to which a product or system has attributes that make it easy to operate and control" [76]. Many researchers have recognized the importance of operability due to the limited size of the screen as well as the multiple context of the user. In fact, the numerous studies dedicated to mobile usability evaluation have adopted this notion in an unchanged form. For example, according to [77] the quality design of operability has a significant impact on the usability of mobile applications, as well as a positive effect on the perceived ease of use [78].

Understandability has been the subject of evaluation in many different mobile solutions [79], [80], [81]. In determining understandability, some researchers note that understanding is more than just comprehension; it also requires the inclusion of context [82]. Therefore, from the user's perspective, understandability is the ability to comprehend any part of a mobile application without difficulty [83], in any possible context of use. Key considerations for testing and evaluation include navigation, interface consistency, clarity of information, quality of feedback, and language and terminology used [84]. In general, all these terms fall under the category of self-descriptiveness, indicated as a relevant factor contributing to the development of usable mobile applications [85], [86].

Since usability is a function of ease of use that affects user performance and satisfaction [87], it is imperative, especially for mobile applications, to recognize that user experience goes beyond mere functionality. In addition to the core attributes, a holistic approach should also consider ease of use, which appears to be an significant determinant of mobile technology adoption [88], [89], [90]. Regardless of the context of use, usability remains a decisive factor in the overall success of mobile technologies [91].

Note that compared to the QUIM, Baharuddin, and Fabil models, the PACMAD+3 model shares four attributes, namely: Efficiency, Effectiveness, Satisfaction, and Learnability, while with Ammar model only two: Learnability and Operability. The remaining attributes were not included after an analysis. This indicates a partial consensus on usability attributes for mobile applications.

Our study provides the following valuable contributions. First, our review delivers evidence-based information on the attributes used to model mobile usability, as well as attributes identified by other systematic reviews. Such knowledge brings valuable insights to ongoing research, updating existing theory and deepening its understanding. Second, a meta-analysis of the collected information identified an overall trend in the field of mobile usability, revealing a consistent emphasis on effectiveness, efficiency, satisfaction, and learnability as key factors contributing to its measurement and evaluation. Third, further analysis inspired us to extend the PACMAD model to include three additional attributes, including Understandability, Ease of Use, and Operability. With this in mind, we present the PACMAD+3 usability model, which provides a holistic view by covering a total of ten attributes, and three external factors (User, Context, and Task). Together, these three additional attributes complement the PACMAD model, providing a more thorough understanding of the mobile usability landscape and serving as a conceptual framework for both researchers and practitioners. Fourth, we reviewed existing definitions of usability attributes and reformulated their concepts according to the state of the art studies. The revised conceptualizations provide a clear and coherent theoretical form, necessary to translate abstract attributes into tangible notions. This is particularly important in empirical research where attributes need to be turned into specific and measurable variables.

Nevertheless, our study suffers from obvious limitations due to the inherent traits of qualitative research. First, there is the issue of generalizability. Since the data were extracted from both systematic literature reviews and general usability models, this problem was greatly mitigated by relying on findings obtained through inductive reasoning. Second, there is the issue of subjectivity and bias. Naturally, interpretations of data are affected by individual perspectives, experiences, and preconceptions. Despite efforts to maintain rigor and neutrality, the subjective nature of qualitative analysis remains an element of interpretive variability. However, the arguments are supported by the relevant and reliable literature, as the study followed a systematic and transparent analytical approach in accordance with established qualitative research guidelines. Third, there is the issue of replicability. Due to the dynamic and context-dependent nature of the data, one can question the ability to reproduce the research using similar settings. In our study, since we considered an evidence-based resource, along with detailed settings applied at each stage, the replicability of both quantitative and qualitative findings can be achieved.

It's important to note that these limitations do not necessarily make qualitative research less valuable. Rather, we aim to highlight the concerns that might be raised about the reported findings. Nevertheless, there is a need to validate our model empirically, with particular focus on the three promoted attributes. In particular, in the future research one could test and evaluate their validity and applicability. With the observed increased attention to mobile applications, especially the factors that influence user adoption, the PACMAD+3 model can serve as a theoretical foundation for the design and development of a research instrument. In this sense, more empirical evidence is needed to assess the impact of each attribute in order to inform both researchers and practitioners about its true value from a user perspective.

VII. CONCLUSION

This study attempts to investigate mobile usability by reviewing the current literature with the goal of developing a comprehensive, unified, and universal model. For this purpose, a qualitative approach was used due to the large amount of research in this area. A systematic literature review was conducted using bibliometric data extracted from the Scopus database, which yielded eight papers on mobile usability models and reviews. A research synthesis of this input allowed us to consolidate and identify the most relevant. In further analysis, the PACMAD model was also identified and incorporated due to its wide adoption and use. As a result, a new unified model consisting of ten usability attributes was established and named PACMAD+3.

The most common goal expressed in usability studies concerns its measurement and evaluation. We believe that PACMAD+3 would pave the way for future researchers wishing to conduct empirical research in this area. Considering that both new attribute names and definitions have been introduced, there is a need to revisit existing scales, as well as to operationalize other scales from scratch, which together raise an interesting and valuable research avenue to undertake. Moreover, since our model is open and generic by nature, the other attributes can also be included, tested, and evaluated, extending the typical scope of research by incorporating context-specific qualities.

On the other hand, one could consider selected usability attributes, as not every study requires such a comprehensive approach. In fact, in mobile usability studies it is crucial to formulate the research objectives with clarity and precision in order to guide the study effectively. For example, a study might prioritize the investigation of satisfaction and understandability, tailoring the scope of the study to user attitudes that can inform targeted improvements. Such an approach not only reinforces the effectiveness of the study, but also ensures that the results are directly applicable.

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