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Usability of mobile applications: literature review and rationale for a new usability model

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Abstract

The usefulness of mobile devices has increased greatly in recent years allowing users to perform more tasks in a mobile context. This increase in usefulness has come at the expense of the usability of these devices in some contexts. We conducted a small review of mobile usability models and found that usability is usually measured in terms of three attributes; effectiveness, efficiency and satisfaction. Other attributes, such as cognitive load, tend to be overlooked in the usability models that are most prominent despite their likely impact on the success or failure of an application. To remedy this we introduces the PACMAD (People At the Centre of Mobile Application Development) usability model which was designed to address the limitations of existing usability models when applied to mobile devices. PACMAD brings together significant attributes from different usability models in order to create a more comprehensive model. None of the attributes that it includes are new, but the existing prominent usability models ignore one or more of them. This could lead to an incomplete usability evaluation. We performed a literature search to compile a collection of studies that evaluate mobile applications and then evaluated the studies using our model.

Introduction

Advances in mobile technology have enabled a wide range of applications to be developed that can be used by people on the move. Developers sometimes overlook the fact that users will want to interact with such devices while on the move. Small screen sizes, limited connectivity, high power consumption rates and limited input modalities are just some of the issues that arise when designing for small, portable devices. One of the biggest issues is the context in which they are used. As these devices are designed to enable users to use them while mobile, the impact that the use of these devices has on the mobility of the user is a critical factor to the success or failure of the application.

Current research has demonstrated that cognitive overload can be an important aspect of usability [1,2]. It seems likely that mobile devices may be particularly sensitive to the effects of cognitive overload, due to their likely deployment in multiple task settings and limitations of size. This aspect of usability is often overlooked in existing usability models, which are outlined in the next section, as these models are designed for applications which are seldom used in a mobile context. Our PACMAD usability model for mobile applications, which we then introduce, incorporates *cognitive load* as this attribute directly impacts and may be impacted by the usability of an application.

A literature review, outlined in the following section, was conducted as validation of the PACMAD model. This literature review examined which attributes of usability, as defined in the PACMAD usability model, were used during the evaluation of mobile applications presented in a range of papers published between 2008 and 2010. Previous work by Kjeldskov & Graham [3] has looked at the research methods used in mobile HCI, but did not examine the particular attributes of usability incorporated in the PACMAD model. We also present the results of the literature review.

The impact of this work on future usability studies and what lessons other researchers should consider when performing usability evaluations on mobile applications are also discussed.

Background and literature review

Existing models of usability

Nielsen [4] identified five attributes of usability:

- Efficiency: Resources expended in relation to the accuracy and completeness with which users achieve goals;

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- Satisfaction: Freedom from discomfort, and positive attitudes towards the use of the product.
- Learnability: The system should be easy to learn so that the user can rapidly start getting work done with the system;
- Memorability: The system should be easy to remember so that the casual user is able to return to the system after some period of not having used it without having to learn everything all over again;
- Errors: The system should have a low error rate, so that users make few errors during the use of the system and that if they do make errors they can easily recover from them. Further, catastrophic errors must not occur.

In addition to this Nielsen defines **Utility** as the ability of a system to meet the needs of the user. He does not consider this to be part of usability but a separate attribute of a system. If a product fails to provide utility then it does not offer the features and functions required; the usability of the product becomes superfluous as it will not allow the user to achieve their goals. Likewise, the International Organization for Standardization (ISO) defined usability as the "Extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [5]. This definition identifies 3 factors that should be considered when evaluating usability.

- User: Person who interacts with the product;
- Goal: Intended outcome;
- Context of use: Users, tasks, equipment (hardware, software and materials), and the physical and social environments in which a product is used.

Each of the above factors may have an impact on the overall design of the product and in particular will affect how the user will interact with the system. In order to measure how usable a system is, the ISO standard outlines three measurable attributes:

- Effectiveness: Accuracy and completeness with which users achieve specified goals;
- Efficiency: Resources expended in relation to the accuracy and completeness with which users achieve goals;
- Satisfaction: Freedom from discomfort, and positive attitudes towards the use of the product.

Unlike Nielsen's model of usability, the ISO standard does not consider Learnability, Memorability and Errors to be attributes of a product's usability although it could be argued that they are included implicitly within the definitions of Effectiveness, Efficiency and Satisfaction. For example, error rates can be argued to have a direct effect on efficiency.

Limitations for mobile applications

The models presented above were largely derived from traditional desktop applications. For example, Nielsen's work was largely based on the design of telecoms systems, rather than computer software. The advent of mobile devices has presented new usability challenges that are difficult to model using traditional models of usability. Zhang and Adipat [6] highlighted a number of issues that have been introduced by the advent of mobile devices:

- Mobile Context: When using mobile applications the user is not tied to a single location. They may also be interacting with nearby people, objects and environmental elements which may distract their attention.
- Connectivity: Connectivity is often slow and unreliable on mobile devices. This will impact the performance of mobile applications that utilize these features.
- Small Screen Size: In order to provide portability mobile devices contain very limited screen size and so the amount of information that can be displayed is limited.
- Different Display Resolution: The resolution of mobile devices is reduced from that of desktop computers resulting in lower quality images.
- Limited Processing Capability and Power: In order to provide portability, mobile devices often contain less processing capability and power. This will limit the type of applications that are suitable for mobile devices.
- Data Entry Methods: The input methods available for mobile devices are different from those for desktop computers and require a certain level of proficiency. This problem increases the likelihood of erroneous input and decreases the rate of data entry.

From our review it is apparent that many existing models for usability do not consider mobility and its consequences, such as additional cognitive load. This complicates the job of the usability practitioner, who must consequently define their task model to explicitly include mobility. One might argue that the lack of reference to a particular context could be a strength of a usability model provided that the usability practitioner has the initiative and knows how to modify the model for a particular context.

Methods

Overview

The PACMAD usability model aims to address some of the shortcomings of existing usability models when applied to mobile applications. This model builds on existing theories of usability but is tailored specifically for applications that can be used on mobile devices. The PACMAD usability model is depicted in Figure 1 side by side with Nielsen's and the ISO's definition of usability. The PACMAD usability model incorporates the attributes of both the ISO standard and Nielsen's model and also introduces the attribute of cognitive load which is of particular importance to mobile applications. The following section introduces the PACMAD usability model and describes in detail each of the attributes of usability mentioned below as well as the three usability factors that are part of this model: user, task and context.

The PACMAD usability model for mobile applications identifies three factors (User, Task and Context of use) that should be considered when designing mobile applications that are usable. Each of these factors will impact the final design of the interface for the mobile application. In addition to this the model also identifies seven attributes that can be used to define metrics to measure the usability of an application. The following section outlines each of these factors and attributes in more detail.

Factors of usability

The PACMAD usability model identifies three factors which can affect the overall usability of a mobile application: *User*, *Task* and *Context of use*. Existing usability models such as those proposed by the ISO [5] and Nielsen [4] also recognise these factors as being critical to the successful usability of an application. For mobile applications *Context of use* plays a critical role as an application may be used in multiple, very different contexts.

User It is important to consider the end user of an application during the development process. As mobile applications are usually designed to be small, the traditional input methods, such as a keyboard and mouse, are no longer practical. It is therefore necessary for application designers to look at alternative input methods. Some users may find it difficult to use some of these methods due to physical limitations. For example it has been shown [7] that some Tetraplegic users who have limited mobility in their upper extremities tend to have high error rates when using touch screens and this may cause unacceptable difficulties with certain (usually small) size targets.

Another factor that should be considered is the user's previous experience. If a user is an expert at the chosen task then they are likely to favour shortcut keys to accomplish this task. On the other hand novice users may prefer an interface that is intuitive and easy to navigate and which allows them to discover what they need. This trade-off must be considered during the design of the application.

Task The word *task* refers here to the goal the user is trying to accomplish with the mobile application. During the development of applications, additional features can be added to an application in order to allow the user to accomplish more with the software. This extra functionality comes at the expense of usability as these additional features increase the complexity of the software and therefore the user's original goal can become difficult to accomplish.

For example, consider a digital camera. If a user wants to take a photograph, they must first select between different modes (e.g. video, stills, action, playback, etc.) and then begin to line up the shot. This problem is further compounded if the user needs to take a photograph at night and needs to search through a number of menu items to locate and turn on a flashlight.

Context of use The word *context* refers here to the environment in which the user will use the application. We want to be able to view context separately from both

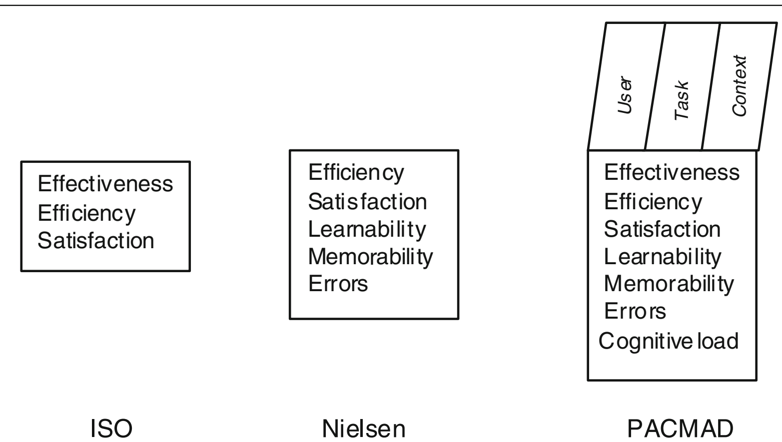

Figure 1 Comparison of usability models.

the user and the task. Context not only refers to a physical location but also includes other features such as the user's interaction with other people or objects (e.g. a motor vehicle) and other tasks the user may be trying to accomplish. Research has shown that using mobile applications while walking can slow down the walker's average walking speed [8]. As mobile applications can be used while performing other tasks it is important to consider the impact of using the mobile application in the appropriate context.

Attributes of usability

The PACMAD usability model identifies 7 attributes which reflect the usability of an application: *Effectiveness*, *Efficiency*, *Satisfaction*, *Learnability*, *Memorability*, *Errors* and *Cognitive load*. Each of these attributes has an impact on the overall usability of the application and as such can be used to help assess the usability of the application.

Effectiveness *Effectiveness* is the ability of a user to complete a task in a specified context. Typically effectiveness is measured by evaluating whether or not participants can complete a set of specified tasks.

Efficiency *Efficiency* is the ability of the user to complete their task with speed and accuracy. This attribute reflects the productivity of a user while using the application. Efficiency can be measured in a number of ways, such as the time to complete a given task, or the number of keystrokes required to complete a given task.

Satisfaction *Satisfaction* is the perceived level of comfort and pleasantness afforded to the user through the use of the software. This is reflected in the attitudes of the user towards the software. This is usually measured subjectively and varies between individual users. Questionnaires and other qualitative techniques are typically used to measure a user's attitudes towards a software application.

Learnability A recent survey of mobile application users [9] found that users will spend on average 5 minutes or less learning to use a mobile application. There are a large number of applications available on mobile platforms and so if users are unable to use an application they may simply select a different one. For this reason the PACMAD model includes the attribute *Learnability* as suggested by Nielsen.

Learnability is the ease with which a user can gain proficiency with an application. It typically reflects how long it takes a person to be able to use the application effectively. In order to measure Learnability, researchers may look at the performance of participants during a series of tasks, and measure how long it takes these participants to reach a pre-specified level of proficiency.

Memorability The survey also found that mobile applications are used on an infrequent basis and that participants used almost 50% of the applications only once a month [9]. Thus there may be a large period of inactivity between uses and so participants may not easily recall how to use the application. Consequently the PACMAD usability model includes the attribute of *Memorability* as also suggested by Nielsen.

Memorability is the ability of a user to retain how to use an application effectively. Software might not be used on a regular basis and sometimes may only be used sporadically. It is therefore necessary for users to remember how to use the software without the need to relearn it after a period of inactivity. Memorability can be measured by asking participants to perform a series of tasks after having become proficient with the use of the software and then asking them to perform similar tasks after a period of inactivity. A comparison can then be made between the two sets of results to determine how memorable the application was.

Errors The PACMAD usability model extends the description of *Errors,* first proposed by Nielsen, to include an evaluation of the errors that are made by participants while using mobile apps. This allows developers to identify the most troublesome areas for users and to improve these areas in subsequent iterations of development. This attribute is used to reflect how well the user can complete the desired tasks without errors. Nielsen [4] states that users should make few errors during the use of a system and that if they do make errors they should be able to easily recover from them. The error rate of users may be used to infer the simplicity of a system. The PACMAD usability model considers the nature of errors as well as the frequency with which they occur. By understanding the nature of these errors it is possible to prevent these errors from occurring in future versions of the application.

Cognitive load The main contribution of the PACMAD model is its inclusion of *Cognitive Load* as an attribute of usability. Unlike traditional desktop applications, users of mobile applications may be performing additional tasks, such as walking, while using the mobile device. For this reason it is important to consider the impact that using the mobile device will have on the performance of the user of these additional tasks. For example a user may wish to send a text message while walking. In this case the user's walking speed will be reduced as they are concentrating on sending the message which is distracting them from walking.

Cognitive load refers to the amount of cognitive processing required by the user to use the application. In traditional usability studies a common assumption is that the user is performing only a single task and can therefore concentrate completely on that task. In a mobile context users will often be performing a second action in addition to using the mobile application [8,10]. For example a user may be using a stereo while simultaneously driving a car. In this scenario it is important that the cognitive load required by the mobile application, in this case the stereo, does not adversely impact the primary task.

While the user is using the application in a mobile context it will impact both the user's ability to move and to operate the mobile application. Therefore it is important to consider both dimensions when studying the usability of mobile applications. One way this can be measured is through the NASA Task Load Index (TLX) [11]. This is a subjective workload assessment tool for measuring the cognitive workload placed on a user by the use of a system. In this paper we adopt a relatively simple view of cognitive load. For a more accurate assessment it may be preferable to adopt a more powerful multi-factorial approach [1,12] but this is beyond the scope of this paper.

Literature review

In order to evaluate the appropriateness and timeliness of the PACMAD usability model for mobile applications, a literature review was conducted to review current approaches and to determine the need for a comprehensive model that includes cognitive load. We focused on papers published between 2008 and 2010 which included an evaluation of the usability of a mobile application.

Performing the literature review

The first step in the literature review was to collect all of the publications from the identified sources. These sources were identified by searching the ACM digital library, IEEE digital library and Google Scholar. The search strings used during these searches were "*Mobile Application Evaluations*", "*Usability of mobile applications*" and "*Mobile application usability evaluations*". The following conferences and journals were identified as being the most relevant sources: the Mobile HCI conference (MobileHCI), the International Journal of Mobile Human Computer Interaction (IJMHCI), the ACM Transactions on Computer-Human Interaction (TOCHI), the International Journal of Human Computer Studies (IJHCS), the Personal and Ubiquitous Computing journal (PUC), and the International Journal of Human-Computer Interaction (IJHCI). We also considered the ACM Conference on Human Factors in Computing Systems (CHI) and the IEEE Transactions on Mobile Computing (IEEE TOMC). These sources were later discarded as very few papers (less than 5% of the total) were relevant.

The literature review was limited to the publications between the years 2008 and 2010 due to the emergence of smart phones during this time. Table 1 shows the number of publications that were examined from each source.

The sources presented above included a number of different types of publications (Full papers, short papers, doctoral consortium, editorials, etc.). We focused the study only on full or short research papers from peer reviewed sources. This approach was also adopted by Budgen et al. [13]. Table 2 shows the number of remaining publications by source.

The abstract of each of the remaining papers was examined to determine if the paper:

1. *Conducted an evaluation of a mobile application/ device;*
2. *Contained some software component with which the users interact;*
3. *Conducted an evaluation which was focused on the interaction with the application or device;*

Publications which did not meet the above criteria were removed.

*The following exclusion criteria were u*sed to exclude papers:

1. *Focused only on application development methodologies and techniques;*
2. *Contained only physical interaction without a software component;*
3. *Examined only social aspects of using mobile applications;*
4. *Did not consider mobile applications.*

Each abstract was reviewed by the first two authors to determine if it should be included within the literature review. When a disagreement arose between the reviewers it was discussed until mutual agreement was

Table 1 Number of publication by source

Source	2008	2009	2010	Total
MobileHCI	107	109	114	**330**
IJMHCI	-	27	19	**46**
TOCHI	24	21	13	**58**
IJHCS	68	78	61	**207**
PUC	54	60	53	**167**
IJHCI	44	37	51	**132**
Total	**297**	**332**	**311**	**940**

Table 2 Number of relevant papers by source

Source	2008	2009	2010	Total
MobileHCI	65	38	46	**149**
IJMHCI	-	22	15	**37**
TOCHI	22	20	12	**54**
IJHCS	64	72	58	**194**
PUC	48	54	50	**152**
IJHCI	37	33	47	**117**
Total	**236**	**239**	**228**	**703**

reached. A small number of relevant publications were unavailable to the authors. Table 3 shows the number of papers included within the literature review by source.

Each of the remaining papers was examined by one reviewer (either the first or second author of this paper). The reviewer examined each paper in detail and identified for each one:

- The attribute of usability that could be measured through the collected metrics;
- The focus of the research presented.
- The type of study conducted;

To ensure the quality of the data extraction performed the first and second author independently reviewed a 10% sample and compared these results. When a disagreement arose it was discussed until an agreement was reached.

Twenty papers that were identified as being relevant did not contain any formal evaluations of the proposed technologies. The results presented below exclude these 20 papers. In addition to this some papers presented multiple studies. In these cases each study was considered independently and so the results based on the number of *studies* within the evaluated papers rather than the number of papers.

Limitations

This literature review is limited for a number of reasons. Firstly a small number of papers were unavailable to the researchers (8 out of 139 papers considered relevant). This unavailability of less than 6% of the papers probably does not have a large impact on the results presented. By omitting certain sources from the study a bias may have been introduced. We felt that the range of sources considered was a fair representation of the field of usability of mobile applications although some outlying studies may have been omitted due to limited resources. Our reviews of these sources led us to believe that the omitted papers were of borderline significance. Ethical approval for this research was given by Oxford Brookes University Research Ethics Committee.

Table 3 Number of publications included within the literature review

Source	2008	2009	2010	Total
MobileHCI	33	11	21	65
IJMCHI	-	6	4	10
TOCHI	2	3	2	7
IJHCS	13	5	4	22
PUC	7	10	4	21
IJHCI	1	2	3	6
Total	**56**	**37**	**38**	**131**

Results

Research questions

To evaluate the PACMAD usability model three Research Questions (RQ1 to RQ3) were established to determine how important each of the factors and attributes of usability are in the context of mobile applications.

RQ1: What attributes are used when considering the usability of mobile applications?

This research question was established to discover what attributes are typically used to analyse mobile applications and which metrics are associated with them. The answers to this question provide evidence and data for the PACMAD usability model.

RQ2: To what extent are the factors of usability considered in existing research?

In order to determine how research in mobile applications is evolving, RQ2 was established to examine the current research trends into mobile applications, with a particular focus on the factors that affect usability.

In addition to this we wanted to establish which research methods are most commonly used when evaluating mobile applications. For this reason, a third research question was established.

RQ3: What research methodologies are used to evaluate the usability of mobile applications?

There are many ways in which mobile applications can be evaluated including controlled studies, field studies, ethnography, experiments, case-studies, surveys, etc. This research question aims to identify the most common research methodologies used to evaluate mobile apps. The answers to this question will throw light on the maturity of the mobile app engineering field.

The above research questions were answered by examining the literature on mobile applications. The range of literature on the topic of mobile applications is so broad it was important to limit the literature review to the most relevant and recent publications and to limit the publication interval to papers published between 2008 and 2010.

RQ1: What attributes are used when considering the usability of mobile applications?

Table 4 shows the percentage of studies that include metrics, such as time to complete a given task, which either directly or indirectly assesses the attributes of usability included within the PACMAD usability model. In some cases the studies evaluated multiple attributes of usability and therefore the results above present both the percentage and the number of studies in which each attribute was considered. These studies often do not explicitly cite usability or any usability related criteria, and so the metrics used for the papers' analyses were used to discover the usability attributes considered. This lack of precision is probably due to a lack of agreement as to what constitutes usability and the fact that the attributes are not orthogonal. The three most common attributes, Effectiveness, Efficiency and Satisfaction, correspond to the attributes identified by the ISO's standard for usability.

One of the reasons these attributes are so widely considered is their direct relationship to the technical capabilities of the system. Both Effectiveness and Efficiency are related to the design and implementation of the system and so are usually tested thoroughly. These attributes are also relatively easy to measure. In most cases the Effectiveness of the system is evaluated by monitoring whether a user can accomplish a pre-specified task. Efficiency can be measured by finding the time taken by the participant to complete this task. Questionnaires and structured interviews can be used to determine the Satisfaction of users towards the system. Approximately 22% of the papers reviewed evaluated all three of these attributes.

The focus on these attributes of usability implies that Learnability, Memorability, Errors, and Cognitive load, are considered to be of less importance than Effectiveness, Efficiency and Satisfaction. Learnability, Memorability, Errors, and Cognitive load are not easy to evaluate and this may be why their assessment is often overlooked. As technology matures designers have begun to consider usability earlier in the design process. This is reflected to a certain extent by technological changes away from command line towards GUI based interfaces.

Table 4 Percentage and number of studies which evaluated each attribute

Attribute	% of studies	Number of studies
Effectiveness	51.15%	67
Efficiency	54.96%	72
Satisfaction	58.02%	76
Learnability	20.61%	27
Memorability	2.29%	3
Errors	32.82%	43
Cognitive Load	22.90%	30

The aspects of usability that were considered least often in the papers reviewed are Learnability and Memorability. There are numerous reasons for this. The nature of these attributes demands that they are evaluated over periods of time. To effectively measure Learnability, users' progress needs to be checked at regular intervals or tracked over many completions of a task. In the papers reviewed, Learnability was usually measured indirectly by the changes in effectiveness or efficiency over many completions of a specified task.

Memorability was only measured subjectively in the papers reviewed. One way to objectively measure Memorability is to examine participants' use of the system after a period of inactivity with the system. The practical problem of recruiting participants who are willing to return multiple times to participate in an evaluation is probably one of the reasons why this attribute is not often measured objectively.

What differentiates mobile applications from more traditional applications is the ability of the user to use the application while moving. In this context, the users' attention is divided between the act of moving and using the application. About 26% of the studies considered cognitive load. Some of these studies used the change in performance of the user performing the primary task (which was usually walking or driving) as an indication of the cognitive load. Other studies used the NASA TLX [11] to subjectively measure cognitive load.

RQ2: To what extent are the factors of usability considered in existing research?

Table 5 shows the current research trends within mobile application research. It can be seen that the majority of work is focused on a *task* approximately 47% of the papers reviewed focus on allowing users to complete a specific task. The range of tasks considered is too broad to provide a detailed description and so we present here only some of the most dominant trends seen within the literature review.

The integration of cameras into mobile devices has enabled the emergence of a new class of application for mobile devices known as augmented reality. For example Bruns and Bimber [14] have developed an augmented reality application which allows users to take a photograph of an exhibit at an art gallery which allows the system to find additional information about the work of art. Similar systems have also been developed for Points of Interest (POIs) for tourists [15].

While using maps is a traditional way of navigating to a destination, mobile devices incorporating GPS (Global Positioning Satellite) technology have enabled researchers to investigate new ways of helping users to navigate.

Table 5 Percentage and number of papers by focus of research

Focus	# of papers	% of papers
Context	11	8.46%
Development Methodology	8	6.15%
Interaction	39	29.77%
Task	61	46.92%
User	12	9.23%
Total	**131**	**100.00%**

A number of systems [16,17] have proposed the use of tactile feedback to help guide users. Through the use of different vibration techniques the system informs users whether they should turn left, right or keep going straight. Another alternative to this is the use of sound. By altering the spatial balance and volume of a user's music, Jones et al. [18] have developed a system for helping guide users to their destination.

One of the biggest limitations to mobile devices is the limited input modalities. Developers of apps do not have a large amount of space for physical buttons and therefore researchers are investigating other methods of interaction. This type of research accounts for approximately 29% of the studies reviewed.

The small screen size found on mobile applications has meant that only a small fraction of a document can be seen in detail. When mobile devices are used navigating between locations, this restriction can cause difficulty for users. In an effort to address this issue Burigat et al. [19] have developed a Zoomable User Interface with Overview (ZUIO). This interface allows a user to zoom into small sections of a document, such as a map, while displaying a small scale overview of the entire document so that the user can see where on the overall document they are. This type of system can also be used with large documents, such as web pages and images.

Audio interfaces [20] are a type of interface that is being investigated to assist drivers to use in-car systems. Traditional interfaces present information to users by visual means, but for drivers this distraction has safety critical implications. To address this issue audio inputs are common for in-vehicle systems. The low quality of voice recognition technology can limit its effectiveness within this context. Weinberg et al. [21] have shown that multiple push-to-talk buttons can improve the performance of users of such systems. Other types of interaction paradigms in these papers include touch screens [22], pressure based input [23], spatial awareness [24] and gestures [25]. As well as using these new input modalities a number of researchers are also looking at alternative output modes such as sound [26] and tactile feedback [27].

In addition to considering the specific tasks and input modalities, a small number of researchers are investigating ways to assist specific types of users, such as those suffering from physical or psychological disabilities, to complete common tasks. This type of research accounts for approximately 9% of the evaluated papers. Approximately 8% of the papers evaluated have focused on the context in which mobile applications are being used. The remaining 6% of studies are concerned with new development and evaluation methodologies for mobile applications. These include rapid prototyping tools for in-car systems, the effectiveness of expert evaluations and the use of heuristics for evaluating mobile haptic interfaces.

RQ3: What research methodologies are used to evaluate the usability of mobile applications?

RQ3 was posed to investigate how usability evaluations are currently conducted. The literature review revealed that 7 of the papers evaluated did not contain any usability evaluations. Some of the remaining papers included multiple studies to evaluate different aspects of a technology or were conducted at different times during the development process. Table 6 shows the percentage of studies that were conducted using each research methodology.

By far the most dominant research methodology used in the examined studies was controlled experiments, accounting for approximately 59% of the studies. In a controlled experiment, all variables are held constant except the independent variable, which is manipulated by the experimenter. The dependant variable is the metric which is measured by the experimenter. In this way a cause and effect relationship may be investigated between the dependant and independent variables. Causality can be inferred from the covariation of the independent and dependent variables, temporal precedence of the cause as the manipulation of the independent variable and the

Table 6 Percentage and number of studies by research methods

Research methods	% of studies	# of studies
Controlled experiment	59.51%	97
Field Study	26.99%	44
Survey	4.29%	7
Case Study	2.45%	4
Informal evaluation	1.84%	3
Archival Research	1.23%	2
Expert evaluation	1.23%	2
Other	2.45%	4
Total	**100%**	**163**

elimination of confounding factors though control and internal validity tests.

Although the most common approach is the use of controlled experiments, other research methodologies were also used. A number of studies evaluated the use of new technologies through field studies. Field studies are conducted in a real world context, enabling evaluators to determine how users would use a technology outside of a controlled setting. These studies often revealed issues that would not be seen in a controlled setting.

For example a system designed by Kristoffersen and Bratteberg [28] to help travellers get to and from an airport by train without the use of paper tickets was deployed. This system used a credit card as a form of ticket for a journey to or from the airport. During the field study a number of usability issues were experienced by travellers. One user wanted to use a card to buy a ticket for himself and a companion; the system did not include this functionality as the developers of the system had assumed each user would have their own credit card and therefore designed the system to issue each ticket on a different credit card.

The evaluation also revealed issues relating to how the developers had implemented the different journey types, i.e. to and from the airport. When travelling to the airport users are required to swipe their credit card at the beginning and end of each journey, whereas when returning from the airport the user only needs to swipe their card when leaving the airport. One user found this out after he had swiped his card to terminate a journey from the airport, but was instead charged for a second ticket to the airport.

Although controlled experiments and field studies account for almost 90% of the studies, other strategies are also used. Surveys were used to better understand how the public reacted to mobile systems. Some of these studies were specific to a new technology or paradigm, [29] while others considered uses such as working while on the move [30]. In two cases (1% of the studies) archival research was used to investigate a particular phenomena relating to mobile technologies. A study conducted by Fehnert and Kosagowsky [31] used archival research to investigate the relationship between expert evaluations of user experience quality of mobile phones and subsequent usage figures. Lacroix et al. [32] used archival research to investigate the relationship between goal difficulty and performance within the context of an on-going activity intervention program.

In some cases it was found that no formal evaluation was conducted but instead the new technology presented in the paper was evaluated informally with colleagues of the developers. These evaluations typically contained a small number of participants and provide anecdotal evidence of a system's usability.

Discussion

The results obtained during the literature review reinforced the importance of cognitive load as an attribute of usability. It was found that almost 23% of the studies measured the cognitive load of the application under evaluation. These results show that current researchers in the area of mobile applications are beginning to recognise the importance of cognitive load in this domain and as such there is sufficient evidence for including it within the PACMAD model of usability.

The results also show that Memorability is not considered an important aspect of usability by many researchers. Only 2% of the studies evaluated Memorability. If an application is easy to learn then users may be willing to relearn how to use the application and therefore Memorability may indeed not be significant. On the other hand, some applications have a high learning curve and as such require a significant amount of time to learn. For these applications Memorability is an important attribute.

The trade-off between Learnability and Memorability is a consideration for application developers. Factors such as the task to be accomplished and the characteristics of the user should be considered when making this decision. The PACMAD model recommends that both factors should be considered although it also recognises that it may be adequate to evaluate only one of these factors depending on the application under evaluation. The literature review has also shown that the remaining attributes of usability are considered extensively by current research. Effectiveness, Efficiency and Satisfaction were included in over 50% of the studies. It was also found the Errors were evaluated in over 30% of these studies.

When considering the factors that can affect usability, it was found that the *task* is the most dominant factor being researched. Over 45% of the papers examined focused primarily on allowing a user to accomplish a task. When the interaction with an application is itself considered as a task this figure rises to approximately 75%. *Context of use* and the *User* were considered in less than 10% of the papers. Context of use can vary enormously and so should be considered an important factor of usability [5,33]. Our results indicate that context is not extensively researched and this suggests a gap in the literature.

It was revealing that some components of the PACMAD model occur only infrequently in the literature. As mentioned above Learnability and Memorability are rarely investigated, perhaps suggesting that researchers expected users to be able to learn to use apps without much difficulty., This finding could also be due to the difficulty of finding suitable subjects willing to undergo experiments on these attributes or the lack of standard research methods for these attributes. Effectiveness, Efficiency, Satisfaction and Errors were investigated more frequently, possibly because these attributes are widely recognised as important, and also possibly because research methods for investigating these attributes are well understood and documented. Almost a quarter of the studies investigated discussed Cognitive Load. It is surprising that this figure is not higher although this could again be due to the lack of a well-defined research methodology for investigating this attribute.

Conclusions

The range and availability of mobile applications is expanding rapidly. With the increased processing power available on portable devices, developers are increasing the range of services that they provide. The small size of mobile devices has limited the ways in which users can interact with them. Issues such as the small screen size, poor connectivity and limited input modalities have an effect on the usability of mobile applications.

The prominent models of usability do not adequately capture the complexities of interacting with applications on a mobile platform. For this reason, this paper presents our PACMAD usability model which augments existing usability models within the context of mobile applications.

To prove the concept of this model a literature review has been conducted. This review has highlighted the extent to which the attributes of the PACMAD model are considered within the mobile application domain. It was found that each attribute was considered in at least 20% of studies, with the exception of Memorability. It is believed one reason for this may be the difficulty associated with evaluating Memorability.

The literature review has also revealed a number of novel interaction methods that are being researched at present, such as spatial awareness and pressure based input. These techniques are in their infancy but with time and more research they may eventually be adopted.

Appendix A: Papers used in the literature review

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Competing interests
The authors declare that they have no competing interests.

Authors' contributions
DF performed the literature review, helped to propose the PACMAD model and drafted the manuscript. RH assisted the literature review, proposed the PACMAD model and drafted the limitations section. DAD helped to refine the conceptual framework and direct the research. All authors read and approved the final manuscript.

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