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LONG PAPER

Development and validation of progressive web application usability heuristics (PWAUH)

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Abstract
Heuristic evaluation (HE) is widely used to evaluate various software, interfaces, systems, or application domains, but using generic heuristics will fail to detect specific usability issues. Researchers currently rely on traditional heuristics such as Nielsen's, SMART, SMASH, or other domain-specific heuristics, which are unsuitable for a modern API system. Although several researchers have successfully developed heuristics specifically for modern systems such as web apps or smartphone apps, there is a lack of specific heuristics for Progressive Web Applications (PWA), a hybrid of native and web apps. Therefore, this paper reports the systematic development of specific heuristics for PWA using a standard eight-step methodology: Exploratory, Experimental, Descriptive, Correlation, Selection, Specification, Validation, and Refinement. The PWA heuristics called PWAUH developed in this study consist of 15 heuristics. We have validated our initial PWAUH with five experts from academia and industry, and the initial 14 heuristics are suitable for further expert validation. Subsequently, PWAUH was further validated using three different PWA domains, cultural heritage, stock photo industry, and marketplace, with sixteen experts ranging from academicians, UX researchers, R&D executives, and postgraduate students in HCI. An additional heuristic is included in the list in the refinement stage. Findings show that PWAUH is effective in identifying usability issues.

Keywords Progressive web applications · Usability heuristic · Heuristic evaluation · Domain-specific heuristics · Heuristic development

1 Introduction

Usability is an attribute that measures the ease of use of an interface through five components: learnability, efficiency, memorability, errors, and satisfaction [1]. Though product usability is often evaluated using usability testing, inspection, or inquiry, it is suggested that usability testing (UT) is the most cost-effective technique for finding usability problems. UT evaluates the entire design to determine the severity of usability issues [2]. Alternatively, heuristic evaluation (HE) is the extensively used inspection method in finding usability problems. It employs principles or heuristics for evaluating usability [3]. Despite criticism for the limited issues identified and the generality of the existing heuristics [4], HE is a popular option due to its cost-effectiveness, ability to be applied in the early stages of development, and convenience in that it does not require any advanced planning to conduct the evaluation [5].

Nielsen's heuristics [6] is the widely used measurement instrument in evaluating software applications. However, previous studies favour using domain-specific heuristics as Nielsen's heuristics are deemed too general for detecting usability issues of a specific system [7–12]. Therefore, domain-specific usability heuristics are required to prevent experts from mapping the usability issues to the wrong category and preventing them from not being able to identify the existing usability problems [13,14]. A few studies have created usability heuristics to cater to their respective domains, recognising a gap in the generic Nielsen's heuristics, for example, website usability heuristics called MiLE + [15], cultural-oriented usability heuristics [9], Smartphone Mobile Application heuRisTics (SMART) [8]; SMArtphone's uSability Heuristics called SMASH [16]; Playability heuristics for mobile games [17]; Mobile map Application heuristics [18]; heuristics for Arabic interface [12]; Playability Heuristics Evaluation for Educational Games (PHEG)

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[11]; Transactional websites heuristics [19]; Grid computing applications [10]; Usability Heuristics for Virtual Worlds [20]. Although Nielsen's heuristics [6] is widely used to assess a web-based application, Joyce and Lilley [8] proposed a specific for native smartphone applications, which are more suitable for smartphone applications. Their study recognised the issues within the traditional usability heuristics, in which smartphone applications are built for small screens and are used in environments that are less constant than desktop applications.

The current study aims to develop novel heuristics for Progressive Web Applications (PWA). A PWA is a web-based application built with a modern and enhanced application programming interface (API) designed to be capable, reliable, and installable to provide a native app-like experience. PWA was introduced by Alex Russell (software engineer at Google) and Frances Berriman (British freelance designer) [21]. Sheppard [22] described PWAs as "a set of strategies, techniques, and APIs" that make the web apps behave or look like native apps. He further explained the four main features of PWA: (1) Offline support: PWAs allow users to load the page even when the users are offline; (2) Performance: PWAs load faster even on a slow network; (3) Home screen icon and splash screen: Home screen can be added to users' home screen without having to go to the web browser, whilst the splash screen feature mimics the native apps feel; (4) Notifications: PWAs support push notifications that can notify users any updates or changes on the app [22]. The many advantages of PWA include being a reliable, fast, and engaging service that allows users to launch web applications from their home screen, cross-platform availability, discoverability, and its ability to keep up-to-date knowledge upon refresh [21, 23–36]. PWA serves as the perfect alternative to the drawbacks of both native and web-based platforms. While the web-based application lacks security, inability to access devices' hardware, and an incomprehensive user experience (UX) when users primarily performed actions or transactions on their mobile devices, the native mobile application was reliable, connectivity dependent, and provided users with an independent experience. It comes, however, with high development prices, is not up to date, and requires more user data and storage.

The PWAs unique features and characteristics have motivated us to investigate whether the existing general and specific heuristics are suitable for evaluating PWAs in HE. We then realised that the existing heuristics for general usability purposes, such as Nielsen's [6], and the specific usability checklists intended for smartphone applications, such as Joyce and Lilley's SMART heuristics [8], are not comprehensive enough for evaluating the PWA due to its unique features. Essentially, PWA is stuck in limbo between smartphone and website characteristics because it is readily available on multiple platforms like websites and can be accessed offline like native apps [37, 38]. The PWAs' main characteristics and features (refer to Table 1 in Sect. 2.1 for more details) motivate us to create a better tool to evaluate the usability of future and existing PWAs as no known study has developed heuristics specifics to the PWAs. In addition, previous researchers [39] compared the UX between PWA, native, and mobile web using ten emotion heuristics developed by [40]. However, no known studies are conducted to integrate the HE in PWA development. In addition, due to the hybrid nature of the PWA, we believe that a specific set of heuristics is required to evaluate applications' usability. PWAs heuristics allow developers/inspectors to identify and fix interaction "problems" with PWAs and subsequently lead to the acceptability of the system by users and provide optimal user experiences (UX) while using PWA. Hence, this study was conducted to bridge the aforementioned gaps.

Furthermore, the systematic literature review conducted by [3, 41] suggested that more than 70 heuristics were developed, and none of them focused on the PWA. A prior literature review on mobile phone heuristics conducted by [42, 43] posited that none of the existing heuristics focused on PWA. Jimenez et al. [42] further explained that most software systems utilised Nielsen's heuristics [6]. Also, to ensure that the developers/inspectors can identify all issues with PWA during HE, it is imperative to have specific heuristics because specific heuristics will help overcome issues of heuristics "too general for detailed analysis" [44] or one heuristics covering a "broad range of usability" [45]. A specific domain heuristic will impact the HE conducted, leading to more consistent and reliable findings across all evaluators [46].

Khan et al. [37] emphasise the importance of PWA by citing a Gartner report indicating that by 2020, 50 per cent of existing native, hybrid, and mobile web applications will be converted into PWA. Despite the statistics of PWA available in the market, and the importance of using a specific heuristic to ensure the effectiveness of the HE, as highlighted by [44, 45, 47], no effort to develop specific heuristics for PWA hinders the effectiveness of the HE. Hence, this study aims to mitigate the aforementioned issues by developing new PWA heuristics.

The study provides new PWA usability heuristics developed using Quinones et al. [48] iterative development guidelines. The guideline comprises eight stages: Exploratory, Experimental, Descriptive, Correlational, Selection, Specification, Validation, and Refinement. The paper is organised as follows. Section 2 establishes the views and background of HE, domain-specific heuristics, PWA, and related studies implementing PWA into their research. Section 3 explains the methodology in PWA heuristics development, whilst Sect. 4 depicts the development and validation of evaluation results. Subsequently, a discussion leads to conclusions and is described in Sect. 5.

Table 1 All about progressive web app

Definition of PWAs	PWAs are developed and improved with newer APIs to provide native-like capabilities by reaching anyone and are reliable and installable on any device [30–32]. Furthermore, a PWA enables regular websites to behave, feel, and look like any other installed app in which a website with a PWA support browser can be added to a device's home screen and used offline
The purpose of PWAs	PWA is developed to give users experiences that are reliable, fast, and engaging. The website loads instantly even in uncertain network conditions; responds fast to user interactions; and engages in such a way that it feels like a natural app on the device itself
Context of use/motivations for developers to implement PWAs	a. The app can be distributed quickly to an even broader user base
	b. It does not require a high budget
	c. There is a limited amount of time available for go-live
	i. A search engine's indexing is critical
	ii. Requires cross-platform compatibility
	iii. More updates are required in a short period
The following literature explains the main features of PWAs [21,23–36]:	a. Responsiveness which can be tailored to the devices, i.e. mobile, desktop, tablet, and others. [21, 27, 28, 36]
	b. Connectivity independent or offline capabilities still work and load even if the device is offline [21, 23, 26–29, 36]
	c. Native App-like, which gave the native apps UX feel [21, 26–28, 31 36]
	d. Information is always updated with push notifications [21, 32, 34] or fresh, which allows checking new updates when online [21, 24, 27, 28, 35]
	e. Safe and secure, whereby the website must run under HTTPS [21, 23, 27–29, 31 33, 36]
	f. Discoverable and identified as "applications" [21, 27, 28] and searchable from Windows 10 marketplace [23]
	g. Re-engageable by keeping it simple to restart the application by implementing a service worker [21, 26, 27]
	h. Installable can be added to the home screen, and users can access the PWA using this shortcut [21, 27, 28, 31]
	i. Linkable, which allows users to easily shared PWA via URL for easy installation [21]
	j. Progressive which works for everyone and is suitable for any browsers preferences [24, 27, 28, 36]
Disadvantages of PWAs	a. Not possible to send push notifications on iOS [23, 78]. It only supports version 11.3 onwards for iOS [79, 80]
	b. Higher usage of device battery [78–80]
	c. Different devices do not fully support all PWA features [36, 79]
	d. It is impossible to create a re-engagement on the iOS platform [79]
	e. There is limited help for offline implementation [79]
	f. Lack of presence in terms of online traffic [79, 80]
	g. There are no regulations or an approval process like native downloadable apps [79]
	h. Limited access to the device's hardware components [40, 61–63-64]
Elements features of PWAs	a. Manifest [29, 32, 81]
	b. Service Workers [25, 26, 28–30, 36, 81]
The installation process	Go to the website- > Add to device home screen—> Open the app—> Use the app

2 Literature review and related works

2.1 Heuristic evaluation and PWA

HE was first introduced by Nielsen and Molich [49] by experimenting with four different user interfaces. They suggested that the number of evaluators required for the evaluation is between three and five. Much later, research suggested that double experts with skills in interface types being evaluated performed better [50], whilst Følstad et al. [51] suggested that domain experts identified equally valid but less through usability issues than the usability experts. In addition, HE is an evaluation technique that requires several experts to identify usability problems according to principles or using a set of usability heuristics [3, 52]. It is a popular evaluation option due to its cost-effectiveness, which is usually related to the number of participants needed, its ability to be implemented in the early stages of development, its convenience whereby it does not require prior advanced planning, and the ability for experts to identify a good number of problems [3, 5]. Although initially intended as 'discount usability engineering' because it did not provide a methodical way of generating solutions to usability problems, nor was it a method to assess product design quality, HE has proved to be a very efficient method, especially in identifying problems with the principles of usability [53]. According to the guidelines, these references will make it easier for developers to redesign the system and fix usability issues.

Wong [54] provided five steps for conducting HE and began selecting evaluators. When evaluating a specific product, researchers should select experts within the domain. Evaluators are briefed on the procedure for HE and the objectives of the evaluation before the evaluation session. Evaluators were asked to explore the interface to understand the system's interaction flow and general overview during the evaluation stage [53]. Subsequently, they ran through and inspected the product, comparing it to a list of usability principles or a specific heuristics guideline. Such domain-specific heuristics may supplement the general Nielsen heuristics or Shneiderman's rule. One approach to assisting evaluators throughout the evaluation process is to supply them with a typical use-case scenario, including the steps a user would perform to execute sample tasks. The next step that follows is recording all the identified problems. The evaluators must be specific when stating a problem and list each usability problem separately. It is done to avoid repeating the new design's problematic aspects and resolve all known usability issues. The HE ends with a debriefing session where evaluators can establish a complete list of problems and suggest potential solutions to those problems.

The need for a novel set of heuristics stems from the belief that traditional Nielsen's heuristics are too general, broad, and lack specificity when evaluating niche applications, despite their time and cost-effectiveness advantages [55]. However, despite all this, studies have been shown to favour using domain-specific heuristics when detecting usability problems [7]. Using a specific heuristics scale can prevent experts from relating usability problems to the wrong category, not identifying usability problems, or not producing quality feedback in terms of finding more severe usability issues [13, 56].

This aim is to develop specific heuristics for PWAs, a new class of web applications that allows the web browser to have the capabilities and perks of the native mobile app by utilising the service workers [30] APIs and Web App Manifests [32]. In addition, we are deeply interested in improving existing heuristics focused on detecting usability problems specific to mobile apps to cater to specific features of PWAs. We have summarised the important information on PWA in Table 1.

Furthermore, we have compared a native app and PWA based on the previous studies on PWA. Table 2 compares a Smartphone native app and a Progressive Web App, whilst Table 3 compares a web app and a native app.

2.2 Related works on existing heuristics

Multiple studies have developed specific usability heuristics for their respective domains, and each of these studies has

Table 3 A comparison between web apps and a native app

Web apps	Features	Native app
Yes	**Quick time to market**	No
Yes	**Requires network access**	Not necessary
Yes	**Inexpensive**	No
No	**Access to device hardware**	Yes
No	**High-quality usability and performance**	Yes
No	**UX & UI standards**	Yes
No	**Security & quality**	Yes

Table 2 A comparison between a smartphone native app and a progressive web app

Native apps	Features	PWA
Individually coded for various platforms (requiring a significant amount of time, effort, and developer knowledge)	**Cross-platform availability**	They are not required to be designed differently or individually [21, 27, 28, 36]
Native apps are more suitable for working offline	**Offline usage**	The intended information will not be displayed in its entirety as it is connectivity independent [21, 23, 26–29, 36]
Drain more battery and use more resources on the device	**Storage, data, and power**	That is not the case. Also use more battery [78– 80]. It is useful in areas where a user might not have a better quality or cheaper data network [21, 23, 26– 29, 36]
Users would have to update the entire application	**Updates**	Users do not need to take any actions to receive updates using push notifications [21, 32, 34]. It also allows checking new updates when online [21, 24, 27, 28, 35]
Limited only to a few browsers	**Push notifications**	Available for all [24, 27, 28, 36]
Adaptiveness and access to device features are limited	**Device features**	Available on the particular platform, for which it was developed.[21, 27, 28, 36]

demonstrated that they are significantly better than general Nielsen's at identifying usability issues. Researchers compared the evaluators' perceptions of the sets of heuristics in terms of Utility, Clarity, Ease of Use, and Necessity of the other checklist as an individual usability heuristic and the Easiness, Usefulness, and Completeness of the heuristics as a whole [57]. Their study reported that generally, the evaluators perceive the Cultural-Oriented Heuristics for e-Commerce and SMASH heuristics as considerably better than Nielsen as they cover more evaluation aspects of the webpage. A more relevant set of heuristics for evaluating mobile applications is called Smartphone Mobile Application Heuristics (SMART), developed by Joyce and Lilley [8]. The heuristics cover the gaps discovered by the generic and other previously developed heuristics for mobile computing and touchscreen-based mobile devices, respectively [58, 59]. The latest study, considered an improvement in SMART heuristics, is called EUHSA [60]. This set of heuristics is built upon the premise that none of the previous studies had assured that the research for mobile heuristics was complete, nor did they comprehensively identify usability issues related to smartphone applications [60]. After conducting a user study to identify and map usability issues with 11 heuristics from previous studies, Bashir and Farooq [60] identified that many usability issues were mapped with 13 heuristics related to smartphone applications with minor changes required in the naming of heuristics, sequencing and heuristic definitions. Their research yielded an utterly new heuristic, "Avoid Misleading Relations", which we are interested in exploring .

Another study relevant to evaluating websites, despite its main issue being controversial in HCI, evaluates the impact of culture on making effective websites as a means of communication between local and global site users [9]. We believe culture is important in designing effective and engaging interfaces. A good web application or focus on e-commerce websites should consider the target users that the site is reaching [9]. The study pointed out that it can be difficult for a platform to encourage users to take advantage of an e-commerce service when the portal suffers from culture-indifferent interface quality. We agree with the authors that the users' demands also increase as the market grows and expands. As a scientific community specialising in human experiences and providing better interaction with computers, we should encourage inclusivity when designing and evaluating products.

Despite heuristic principle similarities in the chosen heuristics, few details have been adjusted in the description of such heuristics to fit into the domain in question. For instance, the Cultural-Oriented Heuristics and EUHSA were developed based on the existing heuristics, including the generic Nielsen's. This explains why these three sets were identical. However, in developing EUHSA, the researchers just based it on Nielsen and SMART [8], SMASH [16, 17], playability heuristics, multi-touch gestures heuristics [61], and many others. We find the approach of Bashir and Farooq's [60] research exciting because they based their heuristics development process on a user study they had before conducted, then mapped the study findings into themes correlated with previously developed themes of heuristics. Their study resulted in a new heuristic on an issue not addressed in other studies, "Avoid misleading relations".

3 Methodology

3.1 Heuristic development methodology

Heuristic development methodology requires researchers to carefully design and follow a systematic and proficient process to ensure all problems can be identified in the early stage of evaluation [62]. Several established methods exist for developing novel heuristics sets, such as [20, 47, 48, 62–64]. However, no agreement exists on which method works better in developing novel heuristic sets [64]. Hence, this study uses a series of methods adopted from Rusu et al. [20], as revised by Quinones et al. [48], which is implemented in this research to develop specific heuristics. The methodology consists of 8 stages: Exploratory, Experimental, Descriptive, Correlational, Selection, Specification, Validation, and Refinement. These stages are summarised in Fig. 1. Quinones and Rusu [47] further explained that although Fig. 1 sequentially shows the stages, the heuristics development can be performed iteratively. Furthermore, some stages can be optional, some overlap, or a stage may stop or return to the previous stage. We have carefully considered these suggestions in our study.

The first stage, the exploratory stage, is the initial phase where the researcher catalogues related information related to the research's main topics. During this stage, a literature review is conducted to obtain information on the application, categorise the application's UX and usability attributes, and identify other heuristics proposed for web-based and native applications.

In the second stage, researchers can analyse the data obtained from previous evaluations in the experimental stage, or perform a new set of evaluations to gather additional information. This stage is optional. For example, Delgado et al. [65] did not perform this stage due to time and resource constraints. In addition, they also performed an extensive literature review and discovered that there were no related studies within the domain in question, making it difficult for them to conduct evaluations. Since we are proposing a new usability heuristic for a relatively new domain, we omitted this stage for a similar reason.

The third stage, descriptive, is where the researchers emphasise the main features discovered in previous research and their context. This stage requires revising the specific usability definition and its characteristics within the digital cultural heritage applications research context.

We describe the domain's information, features, associated usability attributes, existing heuristics, and detected usability problems at this stage. To give meaning and order to the information, we also provide weight or scale in terms of relevance: 3—most relevant, 2—relevant, 1—least relevant, to each element and features regarding the specification of the heuristics. The features collected matched the usability attributes and existing heuristics in the fourth stage (Correlational stage).

The fifth stage (selection) is where we decide whether to keep, adapt, create, or eliminate the selected heuristics. Keep is defined as heuristics that evaluate the application's aspects and usability attributes clearly and correctly. Adapting the heuristic indicates that we will change the existing heuristics to fit into the domain attributes we are evaluating. To delete is to eliminate heuristics we perceive as unrelated to the domain. We create a new heuristic for unmatched features to address usability evaluations.

The specification (stage 6) is where we define the number of heuristics, the elements specifying the heuristics, and formally present the newly proposed heuristics, using guidelines provided by [48] as follows:

- ID (Heuristic identifier), Name & Definition;
- Explanation: Explanation of heuristics concerning usability principles, usability problems, and related heuristics;
- Examples: Examples of usability guidelines or heuristics' violation and fulfilment;
- Benefits: Benefits to be expected if the heuristics are followed;
- Problems: Problems caused by heuristic misunderstandings were anticipated.

The proposed heuristics are subjected to the validation procedures in the validation stage (Stage 7). Depending on the evaluation conducted, we could obtain data on the effectiveness, expert judgments (first evaluation), or user perceptions of the proposed heuristics.

3.1.1 Expert judgement procedure (first evaluation)

The first evaluation aims to gain an expert perception of the proposed heuristic. This evaluation is conducted to elicit experts' opinions on each heuristics principle; assess their perceptions of these four dimensions: utility, clarity, ease of use, and the need for an additional checklist; and have them respond to our questions about the ease of using the set of heuristics, their intention to use the heuristics to evaluate other products in the same domain, and their thoughts on whether the heuristics can cover all usability aspects across different products in the same domain.

The first evaluation in our study examined the heuristics' validity by surveying experts about their perceptions of the proposed heuristics. The following summarises the evaluation's procedures:

(1) Participants recruitment: We have invited five human–computer interaction (HCI) or computer science experts to participate in this evaluation. Participants in the first evaluation consisted of three lecturers with extensive knowledge of HCI (10–15 years of experience) and HE and two UX researchers (3–5 years of experience) from the industry who also have experience conducting HE and other types of evaluation;

(2) Informed consent: All participants were requested to complete the informed consent form before the evaluation and were informed in writing about their rights and data treatment;

(3) Instrument: Participants were asked to complete the questionnaire using the online Google form provided. The form is divided into two sections. In Sect. 1, we aim to obtain participants' feedback in regards to each heuristic' (refer to Table 9) dimensions: utility (D1), clarity (D2), ease of use (D3), and the necessity for more details (D4). In Sect. 2, we aim to get participants' feedback on the heuristics' (1) easiness, (2) overall utility (usefulness), (3) intention for future use, (4) completeness, and (5) quality (need for detailed specifications to understand heuristics). These dimensions and questions were adapted from [48]. In both sections, participants were asked to use a 5-point Likert scale provided (1—Strongly Disagree, 2—Disagree, 3—Neutral, 4—Agree, 5—Strongly Agree);

(4) Expert validation: We conducted this expert validation via an online survey due to the constraints of meeting the experts face-to-face due to the pandemic. Participants were instructed to complete a set of questionnaires comprising four dimensions (D1–D4) using a 5-point Likert scale and five questions as suggested by (Q1–Q5) [48]. They were asked to rate these dimensions.

3.1.2 Second evaluation: heuristic evaluation

The findings of the first evaluation (refer to Table 10 in Sect. 4) were analysed, validating our initial PWAUH. As a result, the initial 14 heuristics are suitable for further expert validation. Subsequently, PWAUH was further validated using three different PWA domains, cultural heritage, stock photo industry, and marketplace, in the second evaluation with sixteen experts ranging from academicians, UX researchers, R&D executives, and postgraduate students in HCI.

Second Evaluation: Heuristic Evaluation (HE) procedure:

(1) Participants recruitment: Fifteen participants were recruited to participate in this evaluation and were recruited using an email invitation. Participants in this evaluation consist of six HCI lecturers (15–21 years of experience), two UX researchers (2–5 years), two R&D executives/e-commerce coordinators (2–5 years of experience), and six postgraduate students in HCI (3 to 6 years of HCI experience). All of them are familiar with HE procedures and have conducted several HE before this study;

(2) Informed consent: All participants were requested to complete the informed consent form before the evaluation and were informed in writing about their rights and data treatment;

(3) Instruments: Participants were asked to use the PWAUH heuristics (refer to Tables 8 and 9) to evaluate the three selected PWAs in this study. They were asked to use the severity rating scale of 0–4 [66] to rate the severity of the usability issues. These ratings are 0, indicating the "problems" was not usability issue, 1 indicating cosmetic issues, 2 indicating minor issues, 3 indicating major issues, and 4 indicating catastrophe issues;

(4) Materials: For the second evaluation for heuristics validation, we conducted a series of heuristic evaluations on 3 PWAs: The Sarawak Digital Cultural Heritage Information System (CULTAGE) as illustrated in Fig. 2, Hermo as shown in Fig. 3, and 123.rf. as shown in Fig. 4. The CULTAGE was developed by researchers in this study for the cultural heritage domain, and additionally, we chose the other two PWA mainly because we want to diversify the types of websites within the domain. In addition, these two sites were chosen because they won first and runner-up among seven other brands for Google Malaysia's Mobile Hackathon in 2017. This event was organised to challenge local developers to build digital experiences and solutions using PWA and Accelerated Mobile Pages (AMP). There were a few reasons for their win: they were able to develop a PWA version of their website, a mobile-friendly, responsive application that allowed users to access their business offerings easily. On top of that, they considered the essential features of PWA, which were to have push notifications and the 'Add to Home screen function. Hermo, on the other hand, is an e-commerce marketplace that has developed an AMP version of its online store, which could be successfully accessible on a low internet connection;

(5) HE Evaluation: Participants were instructed to conduct the HE and email the researchers their HE findings;

(6) Ethical Considerations: While participating in the research process, the researcher must maintain a neutral position, be truthful, and respect the participants' integrity, needs, and privacy [67]. Hence, it is essential to highlight the ethical compliance in completing this study. A University's research ethics guidelines and procedures were strictly followed throughout the research process as the evaluation involved human participants. All participants were informed about their rights before their participation. They were asked to complete the informed consent form before participating in this study. Informed consent is an ethical and legal requirement for any research involving humans because it requires a voluntary agreement from participants [68]. The researcher explains the participants' rights, research procedures, and data treatment during the process. Researchers such as [68–71] explained the importance of providing the informed consent form and data treatment (personal and research data), participants' responsibilities, and rights. In addition, participants are allowed to withdraw at any time without prejudice.

Finally, the Refinement stage (Stage 8) was conducted to change and modify the proposed heuristics based on the suggestions. The methodology suggested creating a refined document that included details heuristics that were refined, created, and/or deleted and why and how they were done.

4 Results

4.1 Progressive Web Application heuristics development

We followed the output recommendations proposed by [47] to present our findings for developing new heuristics for Progressive Web Applications called PWAUH. We are presenting the findings according to the eight stages.

4.2 Stage 1: Exploratory stage

The Exploratory stage (stage 1) involves two major activities as follows.

(1) Exploring the PWA features, related usability, and UX attributes while at the same time examining relevant studies related to heuristic development. This literature review is

presented in Sect. (2.1. Heuristic Evaluation and PWA). The relevant information about PWA is presented in Sect. 2.1.

(2) After reviewing other related literature, we have listed four valuable existing sets of heuristics in developing a set of our own: Three of which are specific to their respective domains (i.e. [8, 9] and [60]) and a generic heuristic (i.e. [6]) that has been widely used in multiple domains web and mobile applications. PWAs are developed and improved with newer APIs to provide native-like capabilities by reaching anyone and are reliable and installable on any device. Specific usability and UX attributes were recorded as follows.

i. Usability principles and usability attributes [1, 72]:
a Learnability—Where new users can engage in meaningful interactions and accomplish the best performances;
b Flexibility—The number of different ways the user and the system exchange data;
c Robustness—The amount of assistance the user gives in making strategies and evaluation goals;
d Efficiency—The speed at which users can perform a task once they learn about the system;
e Memorability—How easily will the user recall the system's functions after a period of inactivity?
f Errors—How many errors do users make, how serious are they, and how easily can users restore from these errors?
g Satisfaction—The extent to which the system can be satisfying to use and satisfy users in terms of usefulness and ease of use.

ii Factors influencing the UX [73]:
a Useful;
b Usable—Usability is concerned with enabling users to accomplish their goals with a product effectively and efficiently;
c Desirable—Design conveys desirability through branding, image, identity, aesthetics, and emotional design;
d Findable;
e Accessible—Accessibility concerns about providing an experience in which users with a different range of physical abilities can access;
f Credible;
g Valuable.

iii Elements of UX [74]:
a Utility: Usefulness; Reliability;
b Usability: Ease of use;
c Social value: Bringing people together; Identifying;
d Enjoyment: Pleasure; Stimulation.

iv Quality in use model (ISO/IEC 25010:2011) [75]: The extent to which different groups could use a product or system to meet everyone's needs and achieve everyone's objectives:
a Effectiveness—The success level when completing a task;
b Efficiency—The less amount of time taken for users to complete a task, the less distraction on users' attention ;
c Learnability—The system should provide informative feedback and allow direct user guidance;
d Operability—The system can adjust and operate on different screens or system compatibility;
e User Error Protection—The extent to which the system can minimise the possibility of user error;
f Freedom from Risk;
g Context Completeness—The extent to which novice users can use the system.

The output from exploratory stages are:

(1) Details about the application (PWA) (refer to section 2.1. for more comprehensive information about PWA);
(2) Usability and UX attributes.

In addition, the following useful sets of heuristics were suggested as a baseline for the next stage:

(1) SMartphone Application HeuRisTics (SMART) [8];
(2) Extending Usability Heuristics for Smartphone Applications (EUHSA) [60];
(3) Cultural-Oriented Heuristics [9];
(4) Nielsen's Usability Heuristics [6].

4.3 Stage 3: Descriptive stage

As explained in 3.1 Heuristic Development Methodology, we have decided to omit stage 2 as we are developing new heuristics. Hence, we move to the *Descriptive* stage (stage 3), whereby we select the information we have previously presented during the exploratory stage according to its importance in developing an evaluation checklist. There are two critical ways of selection. The first entails assigning values to each of the information from the scale: (3) Highly important, (2) Somewhat important, (1) Not important to the domain. The following data were recorded to obtain details on the specific application domain using the scale and are presented in Table 4.

A comparative analysis of existing heuristics was made before prioritising them. As recommended in [48], there

Table 4 Descriptive stage analysis

Category	Value (importance)	Explanation/justification
Definition	**2**	PWAs are developed and improved with newer APIs to provide native-like capabilities by reaching anyone, are reliable, and installable on any device
Context of use	**1**	a.The app is distributed easily to an even broader user base b. It does not require a high budget c. There is a limited amount of time available to go live d. A search engine's indexing is critical e. Requires cross-platform compatibility f. More updates are required in a short period
Areas of use	**1**	a. Social media (e.g. Twitter Lite, Pinterest, Instagram, Tinder) b. Navigation app (e.g.: Google Map) c. Real estate (e.g. Housing.com, Padpiper) d. F&B (e.g. Starbucks) e. E-commerce (e.g.: Digikala) f. Travel (e.g.: MakeMyTrip, Uber) g. Entertainment (e.g. Spotify, Soundslice)
Research justification	**3**	With the increasing Number of PWAs embedded into websites, developers require a specific guideline to assess the usability of their products. Like a cross between a website and a mobile app, the PWA has some features but not others. Furthermore, some PWA features that other heuristics explicitly designed to evaluate mobile apps, such as the classic Nielsen's or SMART, were not considered
Specific domain application features	**3**	a. Elements of PWA: i. Web manifest ii. Service workers iii. The installation process includes: Go to the website- > Add to device home screen—> Open the app—> Use the app b. Features: i. Responsive ii. Connection—independent iii. App-like iv. Safe v. Discoverable vi. Installable vii. Linkable viii. Progressive ix. Re-engageable

Table 4 (continued)

Category	Value (importance)	Explanation/justification
Usability and UX attributes	**3**	a. Dix et al. [72] and Nielsen [1]: i. Learnability ii. Flexibility iii. Robustness iv. Efficiency v. Memorability vi. Errors vii. Satisfaction b. Morville [73]: i. Useful ii. Usable iii. Desirable iv. Findable v. Accessible vi. Credible vii. Valuable c. ISO/IEC 25,010:2011 [75]: i. Effectiveness ii. Efficiency iii. Learnability iv. Operability v. User Error Protection vi. Freedom from Risk vii. Context Completeness
Existing sets of heuristics and/or other relevant elements	**3**	a. Extending Usability Heuristics for Smartphone Application (EUHSA) (**3**) b. SMartphone Application HeuRisTics (SMART) (**3**) c. Cultural-Oriented Heuristics (**3**) d. Nielsen's Usability Heuristics (**1**)

are many sets of existing heuristics in instances where it is not easy to prioritise the sets. Therefore, we compare the heuristics of each set and measure those that evaluate the same criteria or similar definitions. We have decided to use Nielsen's Heuristics [6], Cultural-Oriented Heuristics [9], SMART Heuristics, and EUHSA Heuristics [60] as a baseline for our proposed PWAUH as illustrated in Table 5.

We discovered that comparative analysis could help determine whether the existing heuristics could assess the usability of all the domain's attributes, thereby validating whether we should continue this research. The comparative analysis for existing heuristics is summarised in Table 5.

Comparative analysis assists us in assigning values to these specific heuristics. For example, Visibility of System Status or Providing immediate notification of application status appear in all four sets, emphasising the importance of informing users about product status and changes while in use. As a result, we will prioritise this heuristic by assigning it a score of 3. In

Table 5 Comparative analysis of existing heuristics

Value	Nielsen's heuristics [6]	Cultural-Oriented Heuristics [9]	SMART heuristics [8]	EUHSA heuristics [60]
3	H1: visibility of system status	CH1: visibility of system status	SMART1: provide immediate notification of application status	P1: visibility of system status
3	H2: match between system and the real world	CH2: match between system and the real world	SMART2: use a theme & consistent terms, as well as norms and standards familiar to the user	P2: match between system and the real world
3	H3: user control and freedom	CH3: user control and freedom		P12: user control and obviousness
3	H4: consistency and standards	CH4: consistency and standards		P13: consistency and standards
3	H5: error prevention	CH5: error prevention	SMART3: prevent errors where possible; Assist users should an error occur	P3: realistic error management
1			SMART4: display an overlay pointing out the main features when appropriate or requested	
1			SMART6: design a clear navigable path to task completion	
1				P5: efficiency of use and performance
3	H6: recognition rather than recall	CH6: recognition rather than recall	SMART5: intuitive interfaces make for easier user journeys	P11: recognition rather than recall
3	H7: flexibility and efficiency of use	CH7: flexibility and efficiency of use	SMART7: facilitates effortless input	P7: flexibility and efficiency of use
3	H8: aesthetic and minimalist design	CH8: aesthetic and minimalist design	SMART11: create an aesthetic & identifiable icon	P6: aesthetic and minimalist design
2			SMART9: cater for diverse mobile environments	P8: handling varied contexts of use in mobile environments
2	H9: help users recognise, diagnose, and recover from errors	CH9: help users recognise, diagnose, and recover from errors		
1			SMART8: allow configuration options and shortcuts	
1				P9: fingertip size control and ergonomics
3	H10: help and documentation	CH10: help and documentation		P4: help and documentation
1			SMART10: use the camera, microphone & sensors when appropriate to lessen users' workload	
1		CH11: the information structure		
1		CH12: accurate and detailed results		
1			SMART12: design a visually pleasing interface	
2			SMART13: each interface should focus on one task	P10: effective design to lessen the user's workload
1				P14: avoid misleading relations

cases where we do not find a match for a particular heuristic, we will assign it a value of 1 to indicate that it was developed specifically for the domain and will be further reviewed.

4.4 Stage 4: Correlational stage

We analysed and matched features of our application domain to those with higher priority in the Correlational stage based on the value we assigned to the heuristic in the

Table 6 Results from *Correlational* stage (stage 4)

Features	Attributes	Heuristics
Progressive	Operability (ISO/IEC 25,010:2011) [75] Flexibility [1]	SMART11—Facilitate effortlessness input H7/CH7/P7—Flexibility and efficiency of use SMART5—Intuitive interfaces make for an easier user journey H6/CH6/P6—Recognition rather than recall SMART9—Cater for diverse mobile environments P8—Handling varied contexts of use in mobile environments CH11- Information structure
Connective independent	Use Error Protection (ISO/IEC 25,010:2011) [75] Context completeness (ISO/IEC 25,010:2011) [75]	–
App-like	Satisfaction [1]	H6/CH8/P6—Aesthetic and minimalist design SMART11—Create an aesthetic & identifiable icon SMART12—Design a visually pleasing interface SMART13—Each interface should focus on one task P10—Effective design to lessen the user's workload
Safe	- Credible [73] - Freedom from risk (ISO/IEC 25,010:2011) [75] - Robustness (Nielsen, 2003)	SMART3—Prevent errors where possible; Assist users should an error occur H5 & CH5—Error prevention P3—Realistic error management H9 / CH9—Help users recognise, diagnose and recover from errors
Discoverable	Findable [73]	H2 / CH2 / P2—Match between system and the real world CH4—Consistency & standards SMART2—Use a theme & consistent terms, as well as norms and standards familiar to the user H10/CH10/P4—Help and documentation
Installable	Usable [73]	–
Linkable	Accessible [73]	SMART10—Cater for diverse mobile environments H6/CH6/P11—Recognition rather than recall SMART6—Design a clear navigable path to task completion CH11—Information structure
Responsive	Efficiency [1] Context completeness (ISO/IEC 25,010:2011) [75]	H1/CH1/P1– Visibility of system status SMART1- Provide immediate notification of application status SMART11—Facilitate effortlessness input
Re-engageable	Satisfaction (ISO/IEC 25,010:2011) [75]	H3/CH3—User control and freedom P12—User control and obviousness H7 / CH7 / P7—Flexibility and efficiency of use SMART7—Facilitates effortless input

previous stage. Based on what we have matched, we can determine which feature specific to our domain does not have a heuristic for evaluating it. That is the gap we intend to fill. As a result, we have compiled matched features, attributes, and existing heuristics as depicted in Table 6.

4.5 Stage 5: Selection stage

The Selection stage involved several activities such as sorting and classifying the heuristics by taking actions: Keep, Adapt, Create, and Eliminate. We regard the selection stage as an analytic phase. We investigated which heuristics to

Table 7 Heuristic classification after during selection stage

ID	Heuristics	Action	PWAs features covered
H1/CH1/P1	Visibility of system status	Keep	Responsive
SMART1	Provide immediate notification of application status	Adapt (into H1/CH1/P1)	
H2/CH2/P2	Match between system and the real world	Keep	Discoverable
SMART2	Use a theme and consistent terms as well as norms and standards familiar to the user	Adapt (into H2/CH2/P2)	
H3/CH3	User control and freedom	Delete	–
P12	User control and obviousness	Delete	–
H7/CH7/P7	Flexibility and efficiency of use	Adapt (into SMART7)	Re-engageable
SMART5	Intuitive interfaces make for easier user journeys	Adapt (as *PWA-y*)	Progressive
H6/CH6/P11	Recognition rather than recall		
PWA-y	Intuitive interfaces and navigable paths for easier user journeys	Create	
SMART7	Facilitates effortlessness input	Keep	Progressive–Re-engageable
CH4	Consistency and standards	Keep	Discoverable
CH5	Error prevention	Adapt (into SMART3)	Safe
CH9	Help users recognise, diagnose, and recover from errors		
SMART3	Prevent errors where possible; Assist users should an error occur	Keep	
H6/CH6/P11	Recognition rather than recall	Keep	Linkable
CH8	Aesthetic and minimalist design	Adapt (as *PWA-n*)	App-like
SMART13	Create an aesthetic & identifiable icon		
SMART6	Design a visually pleasing interface		
PWA-n	Identifiable icon & visually appealing interface	Create	
CH10	Help and documentation	Delete	–
CH11	The information structure	Keep	Linkable–Fresh–Progressive
CH12	Accurate and detailed results	Keep	Fresh
SMART4	Display an overlay pointing out the main features when appropriate or requested	Delete	–
SMART9	Allow configuration options and shortcuts	Delete	–
SMART10	Cater for diverse mobile environments	Keep	Progressive–Linkable
SMART13	Each interface should focus on one task	Keep	App-like
H10/CH10/P4	Help and documentation	Keep	Discoverable
PWA-x	Feels native	Create	App-like–Installable– Connection independent

keep, adapt, eliminate, and create based on the features covered and their definition. For example, we decided to keep SMART13: Each interface should focus on one task despite not being highly prioritised at first because the heuristic represents our domain's app-like feature. To avoid information overload and promote a pleasant experience, it is critical for a mobile app's interface presented on the screen to focus on one task.

When we decided to integrate one heuristic into another, as we did with SMART1, Provide immediate notification of application status, we collectively agreed that the visibility of system status heuristics should have the exact definition while being described more clearly. The use context and its relationship with the domain features will be considered in deciding which heuristic to eliminate. For example, the User control and freedom heuristic state that the system should support users to redo or undo their choices tied strongly to having an intuitive and navigable path that promotes an easier user journey. As a result, we recognised that having control and freedom was not as important as providing an option for them to do so as part of their natural journey, resulting in developing a new corresponding heuristic. Table 7 illustrates results from the Selection stage (stage 5).

4.6 Stage 6: Specification stage

During the Specification stage, we decided on the proposed heuristics. In this stage, we specify the list of usability heuristics for Progressive Web Applications (PWAUH). The proposed set of heuristics for PWAUH is depicted in Table 8, whilst Table 9 provides details of these heuristics, including

Table 8 Proposed sets of heuristics (PWAUH)

ID	Heuristics
PWA1	Visibility of system status
PWA2	Match between system and the real world
PWA3	Prevent errors where possible; Assist users should an error occur
PWA4	Consistency and standards
PWA5	Intuitive interfaces and navigable path for the effortless user journey
PWA6	Facilitates effortlessness input
PWA7	Cater for diverse mobile environments
PWA8	Identifiable icon and visually pleasing interface
PWA9	Each interface should focus on one task
PWA10	Recognition rather than recall
PWA11	The information structure
PWA12	Accurate and detailed results
PWA13	Feels native
PWA14	Help and Documentation

Fig. 1 Heuristics Development Methodology (Adapted from [48])

their definitions, explanations, benefits, examples, and evaluation checklist:

4.7 Stage 7: Validation

The Validation stage is divided into two evaluations which involve an experts' validation survey (evaluation 1) and a heuristic evaluation (HE) (evaluation 2).

In the first evaluation (experts' validation survey), we selected five researchers and industry practitioners to participate in our validation survey. An average perception for each PWA usability heuristic is presented in this section. Generally, the heuristics attained high grades (greater than 3.00) with utility dimension (D1) obtaining an average of 4.49, clarity (D2) averaging 4.21, ease of use averaging 4.17, and the need for an additional checklist (D4) with the lowest value averaging 3.13 as illustrated in Table 10.

Unlike the original intention of the dimension (D4), which was to justify the need for the heuristic, we asked the evaluators a different question about the necessity dimension. Our survey asked the evaluators if we should provide more details or additional information in our guidelines to make future evaluations using our usability heuristics easier. It determines whether or not we improve our heuristic definition, explanation, examples, benefits, and checklist. We anticipated a lower average for this specific dimension, which we obtained compared to the others. However, we believe that the template needs to be refined for further evaluation due to the average score of 3.13, which is just above neutral.

In addition, we have calculated the Correlation coefficients between average perception scores of each PWA heuristic, as depicted in Fig. 5. Furthermore, we also calculated the Average perception of overall PWA usability heuristics, as illustrated in Fig. 6.

The correlation coefficient shows that:

1.There is a positive and significant relationship between Utility (D1) and Clarity (D2) with a score of 0.42; if a heuristic is perceived as clear, it is also useful;
2.There is a positive and significant relationship between Clarity (D2) and Ease of Use (D3) with a score of 0.64; when a heuristic is clear, it is easy to be used;
3.There is a strong, positive, and significant relationship between Ease of Use (D3) and Utility (D1) with a score of 0.90; it is very useful when a heuristic is easy to use;
4.There are negative relationships between each dimension and the Need for Additional Checklist (D4). Espe-

Table 9 Details sets of heuristics (PWAUH)

ID	PWA1
Name	Visibility of system status
Definition	The web app must give feedback to ensure users are notified about the changes in processes, status, and activities
Explanation	The system must provide some form of indication of whether an action they have conducted is successful or not
Example(s)	A pop-up message notifies users that their form has been submitted
Benefit(s)	Users are relieved of the burden of worrying about the outcome of their actions
Checklist	1. There is an indication that any changes are being made
	2. The necessary feedback is present for any forms submitted or buttons clicked

ID	PWA2
Name	Match between system and the real world
Definition	The web app should communicate in the users' language through words, phrases, and recognisable ideas, and it should use less technical terms to explain possible actions
Explanation	A system must accommodate a wide range of users with varying backgrounds and levels of technical ability. Therefore, developers should design their system with novice users in mind and use icons familiar to various people
Example(s)	The system uses identifiable icons as back or close buttons
Benefit(s)	Users will not be confused and will feel assured of the functionality behind the icons/buttons
Checklist	1. Icons used are similar to standard icons generally used
	2. The web application displays information in languages that most users can understand
	3. If possible, the web app provides a multilingual function

ID	PWA3
Name	Prevent errors where possible; Assist users should an error occur
Definition	The web app understandably displays an error and suggests a solution to fix it if an error is about to occur
Explanation	Users should be informed of errors, regardless of whether the system or missteps caused them. The system should also avoid letting users perform actions that can lead to errors
Example(s)	When a user's Upload fails, an error message is displayed
Benefit(s)	Keeping users informed
Checklist	1. Buttons and pages in the web app function well
	2. Should an error occur, a message to inform users of the actions they could take is available

ID	PWA4
Name	Consistency and standards
Definition	Regardless of the culture's goal, The system should not leave users wondering whether two actions, situations, or words mean the same thing
Explanation	The system must have a consistent design across its standards, whether synchronicity in the information presented or the result of its action
Example(s)	If a page displays information using a specific layout, information is expected to be presented consistently across all pages
Benefit(s)	Provides structure and consistency in the way information are presented and received
Checklist	1. Consistent result for every similar action taken
	2. The information is presented in a standardised way across all pages

ID	PWA5
Name	Intuitive interfaces and navigable paths for effortless user journeys
Definition	How to interact and navigate the web app to complete a task can be figured out immediately
Explanation	The system's navigation should be straightforward, and users can easily figure out how to accomplish their goals
Example(s)	The user knows how to see the specific information they are looking for, and they will have to click on one of the categorical cards
Benefit(s)	The experience of users using the web app would be pleasurable due to the easy-to-learn interfaces
Checklist	1. The structure of the web app is clearly defined

ID	PWA6
Name	Facilitate effortlessness input
Definition	Ensure that the method for entering data is accurate and straightforward

Table 9 (continued)

ID	PWA6
Explanation	The system could have a large keyboard button, minimum form fields, or multimodal input to ensure that users input their data efficiently and accurately
Example(s)	There is an easy drop-down option for the days, months, and years for forms that require a user to input the date of birth
Benefit(s)	Users can submit their data more efficiently
Checklist	1. A minimal amount of form fields
	2. Browse button to make it easier for users to choose their local data if they need to upload one
	3. Tapping the form fields then activates the phone's keyboard
	4. If users must provide selectable input, they can click on the options or type their inputs

ID	PWA7
Name	Cater for diverse mobile environments
Definition	Interface brightness, sound setting, button size, multimodal input, and output options should be allowed to change according to different contexts and environments of mobile users
Explanation	It is insufficient for the operating system to include its ability to modify the interface's brightness and sound settings. A mobile app developer can further assist users by displaying bigger buttons and multisensory input and output functions
Example(s)	A setting button allows users to mute the background sound in a mobile game, even though users can do it manually on their phones
Benefit(s)	A system that allows flexibility and efficiency gives the user a sense of control
Checklist	1. The web application allows users to change the font size, zoom its display in/out, the level of brightness, or the sound volume

ID	PWA8
Name	Identifiable icon and visually pleasing interface
Definition	The application icon should be identifiable without users looking at the application description. In addition, the interface should be visually pleasing to increase the user's frequency of use
Explanation	The web app's icon must be recognised as it is the first thing the user notices when launching the application or browsing through app stores before the application's title, description, and screenshots. Therefore, aesthetically pleasing interfaces will not only attract more users to use them
Example(s)	Most social media apps have a straightforward interface and icons that are pleasing to users
Benefit(s)	An identifiable icon and a pleasing interface are more memorable, increasing the frequency of use and forgiveness
Checklist	1. It has an appealing interface that does not detract from the app's contents
	2. Identifiable icon that reflects the brand of the system

ID	PWA9
Name	Each interface should focus on one task
Definition	The system should ensure glanceability by displaying only necessary elements on the screen to focus on one task
Explanation	A mobile interface that is less cluttered and simple, with only necessary elements on-screen, allows users to focus on one task. It also ensures that users are not frequently interrupted and that the interface is glanceable
Example(s)	Mobile apps have bars at the bottom or top for users to change pages. It allows users to focus on one page or function at a time
Benefit(s)	Users can focus on one goal at a time
Checklist	1. Functions are listed in a toggle menu or bars, which allows users to choose which page they want to focus on
	2. Web app did not have distracting pop-ups or unnecessary advertisements

ID	PWA10
Name	Recognition rather than recall
Definition	Present elements, activities, and choices obvious to minimise the memory load
Explanation	Users must not be required to memorise in order to execute it. Manuals, instructions, or FAQs should be easily retrievable or visible whenever appropriate
Example(s)	The e-commerce website has recently viewed items to show users what they recently viewed and remind them what they thought of buying
Benefit(s)	Giving options and reminders to users lessens the user's memory load

Table 9 (continued)

ID	PWA10
Checklist	1. Breadcrumbs for users to follow and options to choose from to help them execute actions
ID	PWA11
Name	The information structure
Definition	The information architecture of a website should be in a hierarchical manner from general to specific
Explanation	Information architecture plays a vital role in organising the way information is categorised and displayed to users
Example(s)	In blogs, posts are represented by titles and managed into months of the year
Benefit(s)	A sense of structure will help the users receive the information easily
Checklist	1. Presenting information into categories and sub-categories
	2. There is straightforward navigation for users from the main page
ID	PWA12
Name	Accurate and detailed results
Definition	Task users should be oriented toward the system's goals. For example, search results are shown in an organised and short form to provide a function to the user
Explanation	Depending on a system's goal, a user can be assured that the information presented in a web app is fresh and robust
Example(s)	Search engines like Google ensure that information is updated accordingly to ensure that users can obtain accurate and detailed search results
Benefit(s)	Robustness gives assurance to users that the site is trustworthy and dependable
Checklist	1. Information is being kept up to date
	2. The information system verifies and provides details about data accuracy
ID	PWA13
Name	Feels native
Definition	A progressive web application has to feel as native as an actual mobile application
Explanation	Feeling like a native is a necessary feature of a progressive web app. A good PWA must load quickly, provide an excellent offline experience, use less data, and take up less storage than a native app
Example(s)	Twitter offers a progressive web app called Twitter Lite, which runs on mobile browsers. It takes up only 1 MB of the user's storage space
Benefit(s)	The progressive web app allows users to have the pleasing experience of a native app without demanding any storage capacity. All users across different operating systems can have access to it
Checklist	1. Has to add to Home screen button
	2. Has an identifiable icon
	3. Information is accessible despite a low to no internet connection
ID	PWA14
Name	Help and documentation
Definition	A PWA must offer easy-to-find documentation revolving around users' current tasks
Explanation	Help is being offered in the form of concrete and adequate documentation
Example(s)	Providing Frequently Asked Questions (FAQs) ensures users can easily access them
Benefit(s)	To avoid frustration and confusion whenever users encounter problems
Checklist	1. Providing FAQs / Virtual assistants on the application
	2. The help & documentation function can be found easily in the application

cially a strong negative correlation between D2 and D4 of -0.95. These negative correlations indicate that no other checklist should be needed when a heuristic is clear.

Evaluation 2 (Heuristic evaluation):

Table 11 summarises the demographic analysis of all participants involved in HE.

For Sarawak Digital Cultural Heritage Information System (CULTAGE), 63 problems were identified by evaluators. Of the sixty-three problems, five were rated 4 (Usability catastrophe), which means these problems needed a crucial fix before the product could be released. Nine problems received a rating of 3, indicating major

Table 10 Average perception of each PWA usability heuristic from expert validation surveys

Heuristics	D1 (utility)	D2 (clarity)	D3 (Easy to use)	D4 (Need for additional checklist)
PWA1	4.4	4.6	4.2	3.4
PWA2	4.4	4.6	4.4	2.6
PWA3	4.6	4.6	4.6	3
PWA4	4.6	4.2	4.2	3.6
PWA5	4.4	3.8	4	4
PWA6	4.2	4	4.4	2.8
PWA7	4.6	4.2	4	3
PWA8	4.6	4	4	3.4
PWA9	4.6	4.2	4.2	2.8
PWA10	4.6	4.2	4.2	3
PWA11	4.6	4.4	4.2	2.8
PWA12	4.8	4.2	5	3
PWA13	4.6	4	4.2	3.4
PWA14	3.8	4.2	3.8	3

usability problems which require an important fix. Most of the usability issues identified are categorised under minor usability problems (34) and cosmetic problems (15).

Thirty-one usability problems were identified on the Hermo PWA. Four problems were rated as usability catastrophes; six were listed as having major usability problems, eleven minor usability problems, and ten cosmetic problems .

The 123.rf PWA had forty-one usability problems identified. However, the 123.rf received the most major usability issue rating out of the three PWA evaluated. In addition, from the 41 usability problems, eleven issues needed a crucial fix before the product could be released, fifteen issues should be prioritised for an important fix, nine minor problems, and eight cosmetic issues. Table 14 summarises the findings obtained from the second evaluation of heuristic validation. Detailed findings from HE for Sarawak Digital Cultural Heritage-PWA (CULTAGE), Hermo PWA, and 123rf-PWA are referred to in Appendices 15, 16, and 17, respectively.

Findings from the HE of Sarawak Digital Cultural Heritage-PWA (CULTAGE) (Appendix 15) show that several issues could not be mapped with any PWAUH heuristic, and it was suggested to add another heuristic called readability.

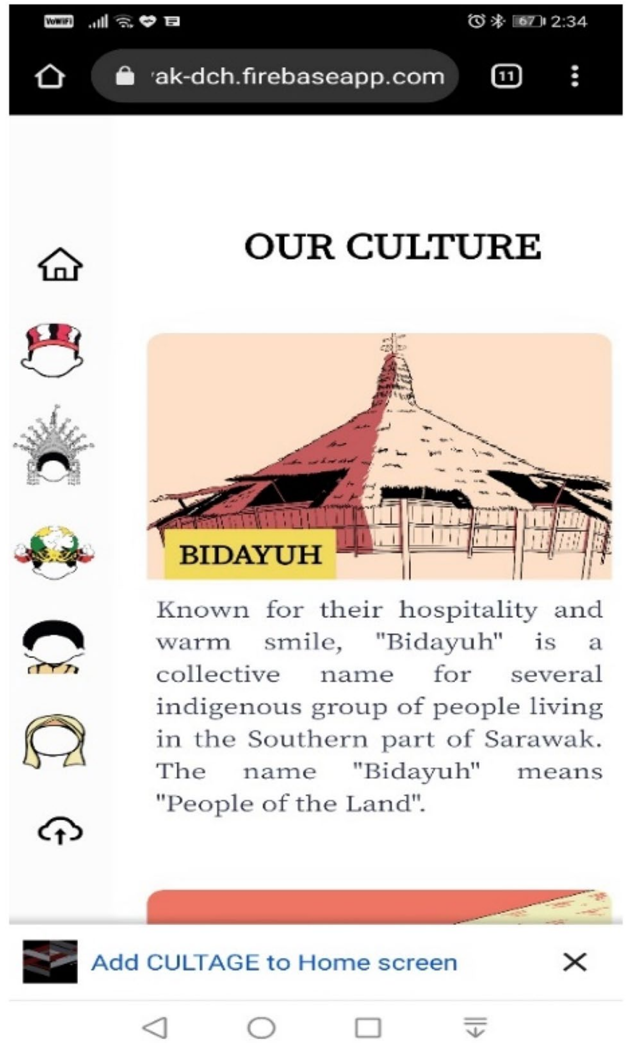

Fig. 2 CULTAGE

4.8 Stage 8: Refinement stage

We further refined our PWAUH based on the findings from the validation stage. As a result, an additional heuristic was added to the list of PWA15 readability in stage 8 (refined stage). Although this heuristic is only visible for CULTAGE PWA, and the severity issues are either 1 or 2, it does show it is vital to deliver a good UX with PWA. Furthermore, some of the issues could also be mapped with PWA4, but we believe that having additional heuristics called PWA15 readability will help identify the usability issues. Table 12 shows an additional heuristic for PWAUH, whilst Table 13 summarises the final PWAUH heuristics.

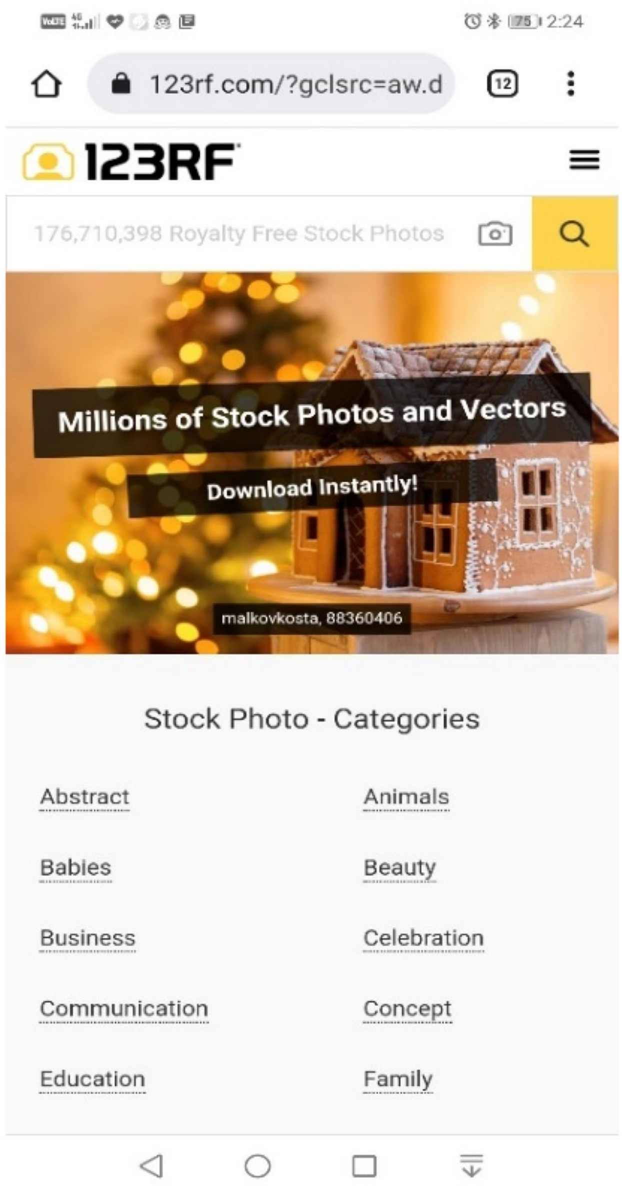

Fig. 3 Hermo

Fig. 4 123.rf

5 Discussion

Our study provides novel heuristics for PWAs, as illustrated in Table 13, using a comprehensive heuristics development methodology suggested by Quinones et al. [48]. We believe this refined PWAUH would greatly benefit researchers, developers, and industry in effectively conducting HE and can identify all issues with PWA during HE. As a result, the users can have a better UX with the product (PWAs). Furthermore, these heuristics will help the developers deliver a well-designed product without compromising the quality, significantly improving the UX for universal access in the information society. The well-defined heuristics will benefit HE as they contribute to the well-planned HE, which helps design iterations [76]. Also, the specific heuristics will help overcome issues highlighted, such as heuristics being "too general for detailed analysis" [44] or one heuristic covering a "broad range of

		Mean_Utility	Mean_Clarity	Mean_EaseOfUse	Mean_NeedForAdditionalChecklist
Mean_Utility	Pearson Correlation	1	.426	.904*	-.353
	Sig. (2-tailed)		.474	.035	.560
	N	5	5	5	5
Mean_Clarity	Pearson Correlation	.426	1	.638	-.950*
	Sig. (2-tailed)	.474		.247	.013
	N	5	5	5	5
Mean_EaseOfUse	Pearson Correlation	.904*	.638	1	-.663
	Sig. (2-tailed)	.035	.247		.222
	N	5	5	5	5
Mean_NeedForAdditionalChecklist	Pearson Correlation	-.353	-.950*	-.663	1
	Sig. (2-tailed)	.560	.013	.222	
	N	5	5	5	5

*. Correlation is significant at the 0.05 level (2-tailed).

Fig. 5 Correlation coefficients scores between average perception scores of each PWA heuristic

	HOW EASY WAS IT TO EVALUATE PWA USING THIS HEURISTICS	DOES THE SET OF HEURISTICS FACILITATE IN EVALUATING THE PWA?	HOW PROBABLE IS THAT THE SET OF HEURISTICS WHEN EVALUATING OTHER PWAS?	DOES THE SET OF HEURISTICS COVER ALL ASPECTS OF THE PWA?	IS A MORE DETAILED SPECIFICATION OF HEURISTICS REQUIRED FOR BETTER UNDERSTANDING?
Mean	4.2000	4.4000	3.8000	4.2000	3.6000
N	5	5	5	5	5
Std. Deviation	.44721	.54772	.44721	.83666	1.14018

Fig. 6 Average perception of overall PWA usability heuristics

Table 11 Demographic analysis

Participant category	Total participants	Years of experience
University Lecturers in HCI	6	15 to 21 years
UX Researchers	2	2–5 years
Research and Development executives/e-commerce coordinator	2	2–5 years
Graduate Students in HCI	6	3–6 years

usability" [45]. In addition, having a specific domain heuristic will reduce the analysis space, results are consistent or "severe issues will likely be missed", which translates to using fewer usability experts or, if conducted by novices, can provide more reliable findings [46].

Given that PWAs are increasingly popular with the statistics by [37] have shown a significant increase in PWAs usage within the last five years, it is vital to have novel heuristics that focus on these PWAs in this evolving information society for a better UX. We intended to close the

Table 12 Summary of heuristic evaluation results

Severity of usability problems	Number of problems identified
Sarawak digital cultural heritage PWA	
4 = Usability catastrophe	5
3 = Major usability problem	9
2 = Minor usability problem	34
1 = Cosmetic problem only	15
Total problems identified:	**63**
Hermo PWA	
4 = Usability catastrophe	4
3 = Major usability problem	6
2 = Minor usability problem	11
1 = Cosmetic problem only	10
Total problems identified:	**31**
123.rf PWA	
4 = Usability catastrophe	11
3 = Major usability problem	15
2 = Minor usability problem	9
1 = Cosmetic problem only	6
Total problems identified:	**41**

gap by conducting this study. In this regard, we argue that the proliferation of technology and its enablers will change how users access and use technology in the information society, and more efforts are required to improve PWAs usability. As a result, the PWAs requirements will continue to grow, require more robust usability heuristics, and require frequent refinement.

Although we have successfully refined our PWAUH heuristics, we also explicitly indicate the steps that must be repeated until we obtain a conclusive set of heuristics. Furthermore, Quinones and Rusu [47] suggested continuously validating and refining heuristics through HE. The methodology recommends performing at least two validation iterations with different evaluations and case studies each time. Furthermore, Yeratziotis and Zaphiris [77] also highlight the importance of refinement through iterations in different phases to ensure high-level heuristics that address the real usability and accessibility issues.

In retrospect, if the heuristics have been validated three times with good results, we can safely assume that the set of heuristics does not always correspond to a new refinement. We believe this comprehensive methodology is appropriate for designing and developing a new usability heuristic checklist due to the precise guidelines provided at each step.

6 Conclusion and future works

Domain-specific usability heuristics are required to prevent experts from incorrectly categorising or identifying existing usability problems. We have successfully developed heuristics for detecting usability issues when evaluating PWAs in this study. In addition, a general overview of the heuristics from our expert validation shows that it received a positive impression for usefulness, clarity, and ease of use, with only a little need for an additional checklist to assist experts in performing a heuristic evaluation using this set of PWA usability heuristics. The heuristics development method employed in this study has yielded novel usability heuristics for PWA consisting of 15 items. We have validated these

Table 13 Additional heuristics

ID	PWA15
Name	Readability
Definition	The information provided should be readable and legible regardless of the density of the page and the screen size
Explanation	The system must acknowledge the importance of the human visual system in which information provided should be readable regardless of the screen sizes used by users, whether it is the font size, the language use, or the choice between text and images
Example(s)	If a page displays information using a specific language, information is expected to be presented consistently across all pages
Benefit(s)	Provides ease of reading across different screen sizes and platforms
Checklist	1. Texts are readable and legible
	2. Provide an option to switch between different languages and avoid the mixture of different languages

Table 14 Final set of heuristics (PWAUH)

ID	Heuristics
PWA1	Visibility of system status
PWA2	Match between system and the real world
PWA3	Prevent errors where possible; Assist users should an error occur
PWA4	Consistency and standards
PWA5	Intuitive interfaces and navigable path for the effortless user journey
PWA6	Facilitates effortlessness input
PWA7	Cater for diverse mobile environments
PWA8	Identifiable icon and visually pleasing interface
PWA9	Each interface should focus on one task
PWA10	Recognition rather than recall
PWA11	The information structure
PWA12	Accurate and detailed results
PWA13	Feels native
PWA14	Help and Documentation
PWA15	Readability

heuristics (PWAUH) for three domains and further refined the developed heuristics. It shows its usefulness and effectiveness in identifying all usability issues. Subsequently, a new heuristic was added to the PWAUH list.

Although this study has successfully delivered new heuristics for PWA using a rigorous systematic development methodology, future work should be considered to refine the PWAUH further. For example, future work could consider replacing the expert with the novice in performing the HE using the new heuristics if the experts are unavailable. Previous studies suggested replacing the expert has a mixed outcome, but it was done using the established heuristics, not the newly developed heuristics. As a result, the authors can compare the finding from HE between the novices and experts for the newly developed heuristics. Furthermore, the researchers believe that the digital native users (novices) are well-versed with the technology and can be easily trained to conduct the HE. Another area for future work that is beneficial for the developers is to explore the collaborative aspect of HE by conducting a collaborative heuristic evaluation (CHE), which is not well explored in the literature. The CHE can also be tested using novices. Although this study has successfully validated the PWAUH across several domains, future work should be conducted to explore the effectiveness of the newly developed heuristics against existing heuristics (i.e. Nielsen, SMART, SMASH, etc.) with different types of PWAs (domain) .

Appendix

See Tables 15, 16, and 17.

Table 15 Findings from HE for sarawak digital cultural heritage-PWA (CULTAGE)

Usability issues	Severity rating	PWA
Glitch issues when clicking the button that shows ethnic categories	4	PWA3
Some of the pictures unable to load	4	PWA14
The search button should be included on the homepage	4	PWA5
Explain a bit the function of the "Contribute" button	4	PWA14
The Home page does not show when first opening the app	4	PWA4
Consistency in displaying different pages in the app (e.g. when I scroll down on the Home page, then I tap on the 'Ulu' button, then the description on the Ulu page does not start from the above. It starts from the middle instead)	3	PWA4
		PWA5
In the menu, I am struggling to know what each icon means. It is true that before we click on the icon, there are some details (e.g. *Orang Ulu*, *Melayu*, etc.), but I only see a glimpse of it before it brings me to the next page. The problem might be major for tourists that do not come from Sarawak because they maybe had no idea what the icon represents	3	PWA5
When I upload the file on the contribute page, I can just upload the image without filling in the details beforehand. So, it might trouble the backend developer of this app when they want to know more details from the user. I suggest it is compulsory to make users fill in the form before they can submit any document	3	PWA3
Contribute page; it is troublesome to rename the file/images because this is a mobile app. So it is not convenient for users. Plus, they have already filled in the form for the app developer to know the details	3	PWA6
		PWA10
The pictures on every page—I have no idea if I can click the photos to bring me to the next page to see further details. I just came to know when I randomly clicked the picture	3	PWA10
The left sidebar menu placement makes it hard for right-handed people to reach it comfortably in one hand	3	PWA5
The left sidebar menu makes the screen looks crowded, and sometimes distracted while trying to focus on the main contents	3	PWA8
Left-handed people will sometimes accidentally click on the icons on the left sidebar many, disrupting the reading experience	3	PWA5
Homepage does not explain the purpose of the web app, and cannot find that information anywhere	3	PWA14
The app does not show any display of the app name (Cultage)	2	PWA14
Inconsistent placeholders on Contribute page. The description does not have any placeholder, while 'Artefact Name' and 'Category' have it	2	PWA5
Unhelpful placeholder on Contribute page. Expecting the placeholder to have examples to assist the user in filling the field	2	PWA5
First-time users would not know immediately that they can also contribute resources, lack awareness	2	PWA14
Curly fonts take a slower time to read, and sometimes it makes the user not want to finish reading it	2	PWA8
The filter function is confusing as users do not know what to filter, expecting options were given	2	PWA6
The filter function does show no result found when an unidentified keyword is added	2	PWA1
Inconsistent icons. Home and Upload are familiar to users but not the culture's icon	2	PWA4
Hard to grasp the hierarchical structure of the web app, no breadcrumb to track progress	2	PWA10
		PWA11
The homepage does not represent a homepage which missing an explanation about the site	2	PWA1
On each explore and sub-explore page, users need to scroll down to see more	2	PWA10
		PWA6
There is no BACK button on explore and sub-explore page	2	PWA5
		PWA10
		PWA6
Images (artefacts, traditional costumes, folklore, ceremonies) used in explore page for all cultures are the same	2	PWA4
The font is too small to describe each culture on explore page	2	PWA4
All images are static—cannot zoom in/out, rotate	2	PWA8
Some of the images are distorted	2	PWA8
Filter artefact—spelling error	2	PWA4
Filter ARTEFACT, unwrap your heritage—jargon term, user, cannot understand or misinterpret	2	PWA2
		PWA4

Table 15 (continued)

Usability issues	Severity rating	PWA
There is no sitemap	2	PWA11
Homepage does not explain what the app is about	2	PWA1
Screen ratio—spaces and white spaces	2	PWA8
Cannot distinguish between the navigation bar and content page	2	PWA8
Navigation bar-slide right for labels but cannot slide left to close it. The expectation would be able to open and close	2	PWA5
Icon and label should be combined. Hidden labels do not serve any critical function	2	PWA5
Font size and text arrangement (CULTAGE button home page)	2	PWA9
Repetition of information on ethnic groups—home page and ethnic group page	2	PWA9
Font too small for ethnic group information at the top page	2	Readability PWA8
Text alignment—blank spaces affect readability	2	Readability PWA8
Title box—extra space	2	PWA8
Grammatical and spelling errors in all sections	2	Readability PWA8
Artefacts—font size and style do not distinguish information hierarchy	2	PWA11
Information repetition to describe different items (e.g. fishing equipment)	2	PWA11
Filter Artefact—no feature/elements selection? No point	2	PWA6
The search box for filter artefact does not show results	2	PWA1 PWA12
Cannot use category links to filter artefact to go to the previous category	1	PWA5
The label 'unwrap your heritage'—meaning not clear	1	PWA2 PWA8
Touching the words initiate Google word search	1	PWA9
Language inconsistency—*Pakaian Lelaki* / Women Traditional Costumes	1	Readability PWA8
Photos are not clear, and images distorted	1	PWA8
Folklores—paragraph alignment. Too much white space	1	Readability PWA8
Too wordy needs visuals	1	Readability PWA8
The wrong category—e.g. types of dances are not traditional ceremonies	1	PWA11
Missing photos—dead links	1	PWA8
inconsistency in categories	1	PWA11
Others' categories—can be categorised	1	PWA11
Contribute page does not align with the screen	1	PWA8
Font style and size need to show the hierarchy of information	1	PWA11 PWA8
Font style and size need to show the hierarchy of task structure	1	PWA11 PWA8
Icon for contributing—meaning not clear	1	PWA8

Table 16 Findings from HE for Hermo-PWA

Usability issues	Severity rating	PWA
The home page and subpage is too long—user need to scroll down	4	PWA10 PWA6 PWA11
Home page—too much information, messy structure	4	PWA10 PWA6 PWA9 PWA11
Some of the pages have no indicator of user location—TOTAL LOST	4	PWA5 PWA11
Unable to open or view the site with no internet connection—something that's expected to be available on PWA (not PWA compliant)	4	PWA13
Error messages are shown inappropriately for sign up—sign up/login was successful, but the error message still appeared	3	PWA3
Main categories and navigation to the main categories of the products are not clearly shown/provided on the main page	3	PWA11
No sitemap on a specific page	3	PWA11
Some of the links on the site lead the user to a blog, exit the website	3	PWA5 PWA9
The tab bar on the PWA is too far below the iPhone, causing the user to bump into the phone's Home bar constantly	3	PWA13
Search results did not reflect keywords/not all related items were shown (e.g. "25 results" but the items displayed are less than that, / "Search result for 'cushion' but somehow toothbrush and eyeliner came up in the list. Since this is a marketplace / online shopping website, stock tagging and categorisation have to be done correctly to avoid customers' frustration	3	PWA12
Some buttons are unresponsive until a few clicks (e.g. Closing pop-ups)	2	PWA5
Buttons for select product variations have almost the same colour. It could raise some issues if people are not aware of it	2	PWA8
Pop-up notification when items have successfully added to the cart is too small	2	PWA1
Not all product details can be directly viewed upon clicking the product picture/name	2	PWA5
Some of the products' information is not directly provided	2	PWA12
Font sizes are too small	2	PWA4 PWA8
Home page—no description of the site	2	PWA1
All images are static—cannot zoom in/out, rotate	2	PWA8
Expecting highlighted information displayed in boxes would be clickable	2	PWA2
Expecting the pictures can be tapped/zoomed in (The native app allows users to do so)	2	PWA8
Expect multiple displayed pictures since it is a marketplace app instead of users needing to tap on "Desc" and "Show more".	2	PWA4 PWA5 PWA6
The "x button" on certain pop-ups/sliders is small and requires users to look out for it	1	PWA5
There is no direct checkout button for individual items to be bought unless the user goes to the cart first	1	PWA4
The top taskbar and second taskbar got quite confusing when the user navigates to "Hermo Global", "Beauty Memo", and "Sale", but the taskbar is still showing the menu/items for other categories	1	PWA8
There are breadcrumbs, but sign out button is not obvious, and the user could not understand the purpose of the attendance button	1	PWA10
No "add to home screen" button when viewed on mobile web	1	PWA13
Help is provided via email, but the availability of the documentation is not very clear	1	PWA14
The "Sort by" bar is awkwardly in the middle of the page as the user scrolls down the list	1	PWA8
Inconsistent display of information some pages use infinite scrolling, and others use pagination	1	PWA4
Choice of button name "Desc" is unclear / a short form, whereas other buttons are spelt correctly	1	PWA4
Breadcrumb when viewing items leads to the items' "Brand" instead of the previous page. For example, iPhone users are expected to swipe left to go back to the previous page. In an app, a back button is expected (Their native app has the back button)	1	PWA10 PWA1

Table 17 Findings for 123rf-PWA

Usability Issues	Severity Rating	PWA
Cannot create a new Likebox, and the app is auto close	4	PWA6
When the heart icon is on the image, the next page shown is the login page (already logged in earlier). I tried to log in using the same credentials earlier but was sent to the wrong password page	4	PWA9
Forget the password page: The error message is "Error: invalid input" when submitting the email address. How to facilitate the reset password process	4	PWA2 PWA3
Camera icon beside the search button on the search bar—what is this camera icon for? Is it for the user to upload photos? Not clear why this icon is here. This is a search bar. If need the user upload their photos, they should have a separate page for this function. Keep the search bar just for search purposes	4	PWA2 PWA5 PWA8 PWA9
The button for Photos, Vectors, Footage, Audio, and Tools that are only visible once the hamburger menu on the top right is tapped needs to be visible so users know these are features available too	4	PWA1 PWA5 PWA10
Users need to scroll down the homepage	4	PWA2
Unnecessary link and menu on the page	4	PWA2
The objective/purpose of the websites is not clear	4	PWA5
On certain pages, no contrast sensitivity between background and font/images	4	PWA8
Webpages are not in a structured layout	4	PWA5 PWA10 PWA11
Unclear link title	4	PWA8
Font sizes are not consistent	3	PWA4
No back button for all the pages except for the home screen	3	PWA4
Contact us page link to email page, but there is no back button to the app, and its app closes automatically	3	PWA5
Likebox page: The three-dot at the right side is not functioning	3	PWA8
No home button; how to return to the start point?	3	PWA1
Search term remains in the search bar field	3	PWA6
The Password field's eye icon is visible only when scrolled to the right	3	PWA1
The side menu is covered by the bottom bar causing cannot click on the "more" function	3	PWA5
The drop-down menu showed the drop-down menu, e.g. the number of people who need to click only a few times. It will confuse the user who navigates	3	PWA1
Some pages are not consistently showing web app interface design. It displays web interface arrangement instead	3	PWA4 PWA7
Some icons are not visible on the 'Blog' page	3	PWA5 PWA8
UI design for the 'Blog' page is inconsistent. Experience for searching blogs is different from searching for photos	3	PWA4
Information (e.g. on-page 'Support' > 'Licensing and Products') is not visibly presented into categories and sub-categories. Users might not know to scroll down for other question options	3	PWA11
Information is not accessible if there is no internet connection	3	PWA13
Redundant page	3	PWA9
Take download pack page takes a long time to load (Buffer)	2	PWA5
There is no help page to support the app usage	2	PWA14
After signing up, there should be an email sent to the email address, but there is none. How do we know if sign-up is successful?	2	PWA1
Once selected, a sub-category of the photo is unclear how to go back to the selected category	2	PWA5
Slow navigation process from pages	2	PWA13
Having an inappropriate placeholder text inside a search box	2	PWA5
There is no clear indicator for the user to go back to the main/previous page after clicking the hamburger menu icon	2	PWA5
No help menu	2	PWA14
Unnecessary buttons "Find out more", "Show more"	2	PWA8

Table 17 (continued)

Usability Issues	Severity Rating	PWA
The menu icon is too small (Difficulty for senior citizens)	1	PWA1
Terms of Use text moves when scrolling up and down, also information in tables that need to be scrolled left/right	1	PWA5
About is at the button of the page, should	1	PWA14
The hamburger menu on the right side is off the norm. Usually, it should be on the left	1	PWA4
Redundant 'Next page' button	1	PWA8
The user has to go all the way down a page in order to navigate to a particular page	1	PWA11

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Nielsen, J.: Usability 101: introduction to usability. Retrieved April 12, 2020, from Nielsen Norman Group website: https://www.nngroup.com/articles/usability-101-introduction-to-usability/ (2012)
2. Nielsen, J.: Usability inspection methods. In: Conference on Human Factors in Computing Systems - Proceedings, 1994 413–414.(1994a) https://doi.org/10.1145/259963.260531
3. Quiñones, D., Rusu, C.: How to develop usability heuristics: a systematic literature review. Comput Stand Interfaces **53**(March), 89–122 (2017). https://doi.org/10.1016/j.csi.2017.03.009
4. Rajanen, M., Rajanen, D.: Heuristic evaluation in game and gamification development. In: GamiFIN Conference, pp. 159–168. Pori (2018)
5. Umar, A., Khan Tatari, K.: Appropriate web usability evaluation method during product development a comparison and analysis of formative web usability evaluation methods. Retrieved from www.bth.se/tek. (2008)
6. Nielsen, J.: Ten usability heuristics. http://designingwebinterfaces.com/6-tips-for-a-great-flex-ux-part-5. (2005)
7. Othman, M.K., Sulaiman, M.N.S., Aman, S.: Heuristic evaluation: comparing generic and specific usability heuristics for identification of usability problems in a living museum mobile guide app. Adv. Hum. Comput. Interact. (2018). https://doi.org/10.1155/2018/1518682
8. Joyce, G., Lilley, M.: Towards the development of usability heuristics for native smartphone mobile applications. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 8517 LNCS(PART 1), pp. 465–474. (2014). https://doi.org/10.1007/978-3-319-07668-3_45
9. Díaz, J., Rusu, C., Pow-Sang, J.A., Roncagliolo, S.: A cultural-oriented usability heuristics proposal. In: ACM International Conference Proceeding Series, (November), 82–87. (2013). https://doi.org/10.1145/2535597.2535615.
10. Quiñones, D., Rusu, C., Roncagliolo, S., Rusu, V., Collazos, C.A.: Formalising the process of usability heuristics development. In: Information Technology: New Generations, pp. 1279–1282. Springer, Cham (2016)
11. Omar, H.M., Jaafar, A.: Conceptual framework for a heuristics based methodology for interface evaluation of educational games. Comput. Inf. Sci. **3**(2), 211 (2010)
12. Muhanna, M.A., Amro, R.N., Qusef, A.: Using a new set of heuristics in evaluating Arabic interfaces. J. King Saud Univ. Comput. Inf. Sci **32**(2), 248–253 (2020)
13. Román-González, M., Pérez-González, J.C., Jiménez-Fernández, C.: Which cognitive abilities underlie computational thinking? Criterion validity of the computational thinking test. Comput. Hum. Behav. **72**, 678–691 (2017). https://doi.org/10.1016/j.chb.2016.08.047
14. Brown, M.: Exploring the advantages of genre specific usability heuristics. Genre **2**(3), 10 (2009)
15. Bolchini, D., Garzotto, F.: Quality and potential for adoption of usability evaluation methods: An empirical study on MiLE+. J. Web Eng., 299–317 (2008)
16. Inostroza, R., Rusu, C., Roncagliolo, S., Rusu, V., Collazos, C.A.: Developing SMASH: a set of SMArtphone's uSability heuristics. Comput. Stand. Interfaces **43**, 40–52 (2016)
17. Korhonen, H., Koivisto, E.M.I.: Playability heuristics for mobile games. In: ACM International Conference Proceeding Series, 159,pp. 9–16. (2006) .https://doi.org/10.1145/1152215.1152218.
18. Kuparinen, L., Silvennoinen, J., Isomäki, H.: Introducing usability heuristics for mobile map applications. In Proceedings of the 26th International Cartographic Conference, August 25 30, 2013, Dresden, Germany, ISBN 978–1–907075–06–3. International Cartographic Association. (2013)
19. Paz, F., Paz, F. A., Pow-Sang, J. A., Collantes, L.: Usability heuristics for transactional websites. In: 2014 11th International Conference on Information Technology: New Generations, pp. 627–628. IEEE (2014)
20. Rusu, C., Roncagliolo, S., Rusu, V., Collazos, C.: A methodology to establish usability heuristics. In: ACHI 2011 : The Fourth International Conference on Advances in Computer-Human Interactions A, pp. 59–62 (2011)
21. Alex Russell.: Progressive Web Apps: Escaping Tabs Without Losing Our Soul. https://infrequently.org/2015/06/ progressive-apps-escaping-tabs-without-losing-our-soul/ (2015). Accessed: July 2nd 2022.
22. Sheppard, D.: Beginning progressive web app development. Apress, Berkeley (2017)
23. Biørn-Hansen, A., Majchrzak, T.A., Grønli, T.-M.: Progressive web apps: the possible web-native unifier for mobile development. (2017) https://doi.org/10.5220/0006353703440351
24. de Andrade Cardieri, G., Zaina, L.M.: Analysing user experience in mobile web, native and progressive web applications: a user and HCI specialist perspectives. In: ACM International Conference

Proceeding Series, 1–11 (2018) https://doi.org/10.1145/3274192.3274201
25. Gauntt, M.: Hackerbits. https://hackerbits.com/wp-content/uploads/2016/12/hacker_bits_issue12.pdf.(2022) Accessed: Accessed: July 2nd 2022
26. Malavolta, I., Procaccianti, G., Noorland, P., Vukmirovic, P.: Assessing the impact of service workers on the energy efficiency of progressive web apps. In: 2017 IEEE/ACM 4th International Conference on Mobile Software Engineering and Systems (MOBILESoft) pp. 35–45. IEEE (2017)
27. Mhaske, A., Bhattad, A., Khamkar, P., More, R.:Progressive web app for educational system. Int. Res. J. Eng. Technol. IRJET,**5**(1). (2018)
28. Tandel, S., Jamadar, A.: Impact of progressive web apps on web app development. Int. J. Innov. Res. Sci. Eng. Technol. **7**(9), 9439–9444 (2018)
29. von der Assen Zurich, J.: A Progressive Web App (PWA)-based Mobile Wallet for Bazo. Retrieved from http://www.csg.uzh.ch/. (2018)
30. Russell, A., Song, J., Archibald,J., Kruisselbrink, M.: Service Workers 1. Editor's Draft, 22 December 2017. W3C. (2017)
31. Steiner, T:. What is in a web view: an analysis of progressive web app features when the means of web access is not a web browser. In: Companion Proceedings of the The Web Conference 2018 pp. 789–796 (2018)
32. Cáceres, M., Christiansen, K. R., Lamouri, M., Kostiainen, A., Dolin, R.: Web App Manifest—Living Document. W3C Working Draft 29 November 2017. W3C (2017)
33. Bateman, A., Koch, Z., McElmurry, R., Denicola, D., Cáceres, M.: Payment Request API. W3C Candidate Recommendation 21 September 2017. W3C. (2017)
34. Beverloo, P., Thomson, M., van Ouwerkerk, M., Sullivan, B., Fullea., E.: Push API. W3C Editor's Draft 15 December 2017. W3C (2017)
35. Petele.: Your First Progressive Web App. https://codelabs.developers.google. com/codelabs/your-first-pwapp/index.html. (2016) Accessed: Accessed: July 2nd 2022.
36. Gambhir, A., Raj, G.: Analysis of cache in service worker and performance scoring of progressive web application. In: 2018 International Conference on Advances in Computing and Communication Engineering (ICACCE) pp. 294–299, IEEE (2018)
37. Khan, A.I., Al-Badi, A., Al-Kindi, M.: Progressive web application assessment using AHP. Procedia Comput. Sci. (2019). https://doi.org/10.1016/j.procs.2019.08.041
38. Hu, K., Zhu, J.: A progressive web application on ancient roman empire coins and relevant historical figures with graph database. In: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11197 LNCS, 235–241 (2018) https://doi.org/10.1007/978-3-030-01765-1_26.
39. de Andrade Cardieri, G., Zaina, L. M.: Analyzing user experience in mobile web, native and progressive web applications: a user and HCI specialist perspectives. In: Proceedings of the 17th Brazilian Symposium on Human Factors in Computing Systems pp. 1–11 (2018)
40. De Lera, E., Garreta-Domingo, M.: Ten emotion heuristics: guidelines for assessing the user's affective dimension easily and cost-effectively. In: Proceedings of HCI 2007 The 21st British HCI Group Annual Conference, pp. 1–4, University of Lancaster, UK 21 (2007)
41. Hermawati, S., & Lawson, G. (2016). Establishing usability heuristics for heuristics evaluation in a specific domain: Is there a consensus? Applied ergonomics, 56, 34–51.https://doi.org/10.1016/j.apergo.2015.11.016.
42. Jimenez, C., Lozada, P., & Rosas, P. (2016, September). Usability heuristics: A systematic review. In: 2016 IEEE 11th Colombian Computing Conference (CCC) (pp. 1–8). IEEE.
43. Dourado, M. A. D. (2018). Usability heuristics for mobile applications a systematic review. https://bdm.unb.br/bitstream/10483/21589/1/2017_MarcosAntonioDourado_tcc.pdf
44. Andre, T.S., Hartson, H.R., Belz, S.M., McCreary, F.A.: The user action framework: a reliable foundation for usability engineering support tools. Int. J. Hum Comput Stud. **54**(1), 107–136 (2001)
45. Sears, A.: Heuristic walkthroughs: finding the problems without the noise. Int. J. Hum. Comput. Interact. **9**(3), 213–234 (1997)
46. Chattratichart, J., Brodie, J.: Extending the heuristic evaluation method through contextualisation. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 46, no. 5, pp. 641–645. CA: SAGE Publications, Sage CA: Los Angeles (2002)
47. Quiñones, D., Rusu, C.: Applying a methodology to develop user eXperience heuristics. Comput. Stand. Interfaces **66**(January), 103345 (2019). https://doi.org/10.1016/j.csi.2019.04.004
48. Quiñones, D., Rusu, C., Rusu, V.: A methodology to develop usability/user experience heuristics. Comput. Stand. Interfaces **59**, 109–129 (2018)
49. Nielsen, J., Molich, R.: Heuristic evaluation of user interfaces. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 249–256 (1990)
50. Nielsen, J.: Finding usability problems through heuristic evaluation. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 373–380 (1992)
51. Følstad, A., Anda, B.C., Sjøberg, D.I.: The usability inspection performance of work-domain experts: an empirical study. Interact. Comput. **22**(2), 75–87 (2010)
52. Yáñez Gómez, R., Cascado Caballero, D., Sevillano, J.-L., Mez, R., Cascado Caballero, D., Sevillano, J., Luis.: Heuristic evaluation on mobile on mobile interfaces: a new checklist. Sci. World J. **2014**, 434326 (2014). https://doi.org/10.1155/2014/434326
53. Nielsen, J.: Heuristic evaluation: how-to: article by Jakob Nielsen. Retrieved April 12, 2020, from Nielsen Norman Group website: https://www.nngroup.com/articles/how-to-conduct-a-heuristic-evaluation/. (1994)
54. Wong, E.: Heuristic evaluation: how to conduct a heuristic evaluation | interaction design foundation. Retrieved April 15, 2020, from https://www.interaction-design.org/literature/article/heuristic-evaluation-how-to-conduct-a-heuristic-evaluation. (2020)
55. International organization for standardization ISO (2011)
56. Jimenez, C., Lozada, P., Rosas, P.: Usability heuristics: a systematic review. In: 2016 IEEE 11th Colombian Computing Conference, CCC 2016 - Conference Proceedings. (2016) https://doi.org/10.1109/ColumbianCC.2016.7750805.
57. Rusu, C., Rusu, V., Quiñones, D., Roncagliolo, S., Rusu, V.Z.: Evaluating online travel agencies' usability: what heuristics should we use?. In: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 10913 *LNCS*, 121–130 (2018). https://doi.org/10.1007/978-3-319-91521-0_10
58. Bertini, E., Gabrielli, S., Kimani, S., Catarci, T., Santucci, G.: Appropriating and assessing heuristics for mobile computing. In: Proceedings of the Workshop on Advanced Visual Interfaces, vol. 2006. https://doi.org/10.1145/1133265.1133291.(2006)
59. Inostroza, R., Rusu, C., Roncagliolo, S., Jiménez, C., Rusu, V. Usability heuristics for touchscreen-based mobile devices.In: Proceedings of the 9th International Conference on Information Technology, ITNG 2012, 662–667 (2012). https://doi.org/10.1109/ITNG.2012.134.

60. Bashir, M.S., Farooq, A.: EUHSA: extending usability heuristics for smartphone application. IEEE Access **7**, 100838–100859 (2019). https://doi.org/10.1109/ACCESS.2019.2923720
61. Humayoun, S.R., Chotala, P.H., Bashir, M.S., Ebert, A.: Heuristics for evaluating multi-touch gestures in mobile applications. In: HCI 2017: Digital Make Believe - Proceedings of the 31st International BCS Human Computer Interaction Conference, HCI 2017, 2017-July.(2017). https://doi.org/10.14236/ewic/HCI2017.89.
62. Somervell, J., McCrickard, D.S.: Better discount evaluation: illustrating how critical parameters support heuristic creation. Interact. Comput. **17**(5), 592–612 (2005)
63. Baker, K., Greenberg, S., Gutwin, C.: Heuristic evaluation of groupware based on the mechanics of collaboration. In: IFIP International Conference on Engineering for Human-Computer Interaction pp. 123–139. Springer, Berlin, Heidelberg (2001)
64. Sim, G., Read, J.C., Cockton, G.: Evidence based design of heuristics for computer assisted assessment. In: IFIP Conference on Human-Computer Interactio*n* pp. 204–216. Springer, Berlin, Heidelberg (2009)
65. Delgado, D., Zamora, D., Quiñones, D., Rusu, C., Roncagliolo, S., Rusu, V.: User experience heuristics for national park websites. In: International Conference on Human-Computer Interaction, pp. 193–204. Springer, Cham (2020)
66. Nielsen, J.: Reliability of severity estimates for usability problems found by heuristic evaluation. In: Posters and short talks of the 1992 SIGCHI conference on Human factors in computing systems pp. 129–130 (1992)
67. Gallegos-Erazo, F.A., Guevara, M.D.F.I., Campoverde, M.A.M.: Ethics and its Importance in Research. In. Álava Alcivar, M.Á. (eds). The Social Sciences and their Contribution to Scientific Research: Empirical Studies, 9–22. (2021)
68. Henry, K.A. (2022) Informed consent and other human subject protection. In: Dubinsky,P.M., Henry K.A. (eds.) The Fundamentals of Clinical Research: A Universal Guide for Implementing Good Clinical Practice, 239–263.
69. Gerard, L., Wiley, K., Debarger, A.H., Bichler, S., Bradford, A., Linn, M.C.: Self-directed science learning during COVID-19 and beyond. J. Sci. Educ. Technol. **31**, 258–271 (2022)
70. Dunlop, A.: Girls and Science: Examining Students' Attitudes and Learning Environment Perceptions (Doctoral dissertation, Curtin University)] (2022)
71. Fink, A.S., Prochazka, A.V., Hall, D.E.: Extending the discussion on informed consent. J. Am. Coll. Surg. **234**(5), 975–976 (2022)
72. Dix, A., Finlay, J., Abowd, G.D., Beale, R.: Human-computer interaction. Pearson Education (2005)
73. Morville, P.: User experience design. Retrieved from http://semanticstudios.com/user_experience_design/. (2004)
74. Roto, V., Rautava, M.: User experience elements and brand promise. In: International Engagability & Design Conference, in Conjunction with NordiCHI, vol 8, (2008)
75. ISO/IEC 25010/2011. System and software engineering- systems and software quality requirements and evaluations (SQuaRE)-system and software quality models. Online: https://www.iso.org/standard/35733.html
76. Cockton, G., Woolrych, A.: Sale must end: should discount methods be cleared off HCI's shelves? Interactions **9**(5), 13–18 (2002)
77. Yeratziotis, A., Zaphiris, P.: A heuristic evaluation for deaf Web user experience (HE4DWUX). Int. J. Hum. Comput. Interact. **34**(3), 195–217 (2018)
78. Lvivity (2022). What is a progressive web app?Pros&Cons of PWA. https://lvivity.com/introduction-to-progressive-web-apps. Accessed: Accessed: July 2nd 2022.
79. Iquii (2019) Progressive Web App (PWA): what they are, pros and cons and the main examples on the market https://medium.com/iquii/progressive-web-app-pwa-what-they-are-pros-and-cons-and-the-main-examples-on-the-market-318f4538c670. Accessed: Accessed: July 2nd 2022.
80. Digital one agency: Progressive WebApps-2020 The Pros and Cons. https://digitaloneagency.com.au/progressive-web-apps-2020-the-pros-and-cons/.(2020). Accessed: Accessed: July 2nd 2022
81. Břoušek, P.: Evaluation and usage of Google Progressive Web Apps technology (Doctoral dissertation, Masarykova univerzita, Fakulta informatiky). (2017)