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Review

Intelligent personal assistants: A systematic literature review

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ABSTRACT

Natural Language Interfaces allow human-computer interaction through the translation of human intention into devices' control commands, analyzing the user's speech or gestures. This novel interaction mode arises from advancements of artificial intelligence, expert systems, speech recognition, semantic web, dialog systems, and natural language processing, bringing the concept of Intelligent Personal Assistant (IPA). There is currently a vast literature on this subject. However, in the best of our knowledge, there is no thorough analysis of the state-of-the-art in the field. In this context, we present in this article a survey of the field, discussing the main trends, critical areas, and challenges of an IPA. Another contribution is the proposition of a taxonomy for IPA classification. The method used to achieve these objectives consisted of a systematic literature review based on the population, intervention, comparison, outcome, and context (PICOC) criteria. As a result, we started from more than 3472 scientific articles published in the last six years, searched on a set of databases chosen to increase the probability of finding highly relevant articles. The review selected the 58 most significant articles, identifying challenges and open questions. We also discuss in the article the current status, usage, security and privacy issues, types, and architectures regarding an IPA. We conclude that usability, security, and privacy directly affect the confidence of the user in adopting an IPA.

1. Introduction

The communication with devices using the voice is nowadays a common task for many people. Intelligent Personal Assistants (IPA), such as Amazon Alexa,[1] Microsoft Cortana,[2] Google Assistant,[3] or Apple Siri,[4] allow people to search for various subjects, schedule a meeting, or to make a call from their car or house hands-free, no longer needing to hold any mobile devices. These intelligent assistants make use of Natural Language User Interfaces (NLUI) to interact with users and provide information about the weather, maps, schedule, call, events, etc. (Santos, Rodrigues, Casal, Saleem, & Denisov, 2017). NLUI allow Human-to-Machine (H2M), Human-Device Interaction (HDI) and Human-Computer Interaction (HCI), which involves the translation of human intention into devices' control commands through speech recognition (Drosdov, Díaz-Sánchez, Almenárez, Arias-Cabarcos, & Marín, 2017). These gadgets present the advancements of artificial intelligence (AI), speech recognition, semantic web, dialog systems, and natural language processing, consolidating the concept of an IPA. The term IPA is known as a system that can understand, respond to spoken inputs, and process the user request (Santos et al., 2017). As people are interacting by voice with an increasing number of devices, the conversation is becoming an essential mode of human-computer interaction (Luger & Sellen, 2016). The benefits are not only voice control but also the dialogue-style nature of the interactions (Kiseleva et al., 2016a).

IPA allows a hands-free human-device interaction, and this technology unleashes the computing to work on new areas not explored yet. For instance, in the health area, a surgeon can check

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[1] Available at https://developer.amazon.com/alexa. Access on October 3rd, 2018.
[2] Available at https://www.microsoft.com/en-us/cortana. Access on October 3rd, 2018.
[3] Available at https://assistant.google.com. Access on October 3rd, 2018.
[4] Available at https://www.apple.com/siri/. Access on October 3rd, 2018.

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the patient's history or exam results during a surgery procedure (Jalaliniya & Pederson, 2015). In sports, an athlete can be monitored, ask, and receive information about his performance during a training or access information about rivals in a competition (Sörös, Daiber, & Weller, 2013). In the education area, IPA can help students to improve their skills in several manners, like learning a second language (Dizon, 2017) or training a new machine maintenance procedure (Zhu et al., 2014). Electronic games, appointments scheduling, weather forecasting, and general questions are other sorts of applications suitable for IPA.

Since the introduction of IPA in the 1990s, many research articles have been published on the subject, including some surveys. Azvine, Djian, Tsui, and Wobcke (2000) present an overview of IPAs types, devices, and user interface, pointing their current challenges. Pokojski (2004) describes the IPA software concepts, including the proposition of a specific approach, and discussing knowledge-based systems. The authors conclude that it is relatively difficult to develop universal intelligent personal assistant software. Another article focuses on comparing personal assistants for understanding the framework design, architecture, and implementations (Ricky & Gulo, 2015). Finally, Costa, Novais, and Julian (2018) explore Cognitive Assistants, which is a subset of IPAs, focusing on ubiquitous and pervasive platforms and services. The article provides a list of new projects, summarizing the state-of-art, and discussing how technology supports the elderly affected by physical/mental disabilities or chronic diseases.

Analyzing all the articles found in this research, no one proposed a systematic literature review aiming to identify different key areas of research on IPAs. According to Budgen and Brereton (2006), a systematic review is a means of identifying, evaluating and interpreting all available research relevant to a particular research question or topic area. A work of this nature is essential to many areas (e.g., artificial intelligence, expert systems, conversational and cognitive agents), because it identifies the leading applications, involved technologies, software architectures, challenges and open questions, and the opportunities regarding IPA. Therefore, the current work aims to discuss the concepts and significant findings regarding IPAs, using this methodology. However, as pointed out in other works (Rattan, Bhatia, & Singh, 2013; Roehrs, da Costa, Righi, & de Oliveira, 2017) the systematic review literature researches have some limitations due to the empowered methodological rigor. Furthermore, the current work is limited to aspects regarding IPA concepts and applications.

The proposed work provides a set of contributions which can be used as directions for future research by the scientific community. As main contributions of the article, we highlight (1) a systematic review of the state-of-the-art related to intelligent personal assistants; (2) a taxonomy to classify the essential characteristics of IPA applications; (3) a mapping of current IPAs usage and domains; (4) a set of opportunities areas to IPA applications; and, (5) an overview of commercial and non-commercial IPA applications.

Intelligent Personal assistants are a particular type of expert system. They use many artificial intelligence concepts to translate hands-free human interaction into a set of understandable computer commands. In this process, different approaches are employed: to convert user utterances into text (Speech Recognition), to classify the words and sentences in semantic structures (Natural Language Understanding), to interact and answer questions of the user (Dialog Management), and to convert back the generated text to voice (Speech Synthesis). Considering the investigated state-of-the-art, this survey points out challenges related to usability, security, and privacy.

The work is organized as follows: Section 2 presents the research method and questions. Following, Section 3 presents the results obtained from the collection of articles and discuss the main findings. The limitations are presented in Section 4 and both challenges and open questions are presented in Section 5. Finally, we discuss the conclusions and directions for future work in Section 6.

2. Material and methods

The current study presents a systematic literature review designed to provide a comprehensive overview of the IPA research area, summarizing the technology regarding IPA and identifying promising directions, without in-depth analysis and synthesis. With this in mind, we followed widely recognized guidelines (Biolchini, Gomes Mian, Candida, Natali, & Travassos, 2005; Kitchenham & Charters, 2007; Petticrew & Roberts, 2006; Roehrs et al., 2017) to plan and run systematic mapping studies. The presented systematic literature review method was carried out through the following activities:

1. Planning the review;
2. Investigation of research questions;
3. Description of both sources of information and strategy used to collect data;
4. Description of additional sources used on data collection;
5. Description of the search criteria for selecting the studies;
6. Definition of the inclusion and exclusion criteria used to filter the studies;
7. Description of the quality assessment of the selected studies;
8. Comparison of selected studies and research questions.

The following sections describe how this process of mapping the study was carried out.

2.1. Planning the review

The review protocol includes the research questions, sources of information, additional sources and the methods used to map the studies in Intelligent Personal Assistants. Also, the review comprises the identification of primary studies, applying inclusion and exclusion criteria and synthesizing the results. In order to reduce researcher bias, one of the authors developed the protocol, the others reviewed and then the authors developed a discussion, review, and iteration. Finally, the authors searched in the databases and reported the results.

2.2. Research questions

Once the definition of research questions is the most crucial part of any systematic review (Kitchenham & Charters, 2007), we aim to identify and classify the existing literature focusing on Intelligent Personal Assistants as well as the emerging features, problems, challenges, solutions, and the research trends. Table 1 describes the general and specific research questions.

In the proposed systematic review, the general research questions have been refined into more specific questions to provide better classification and thematic analysis. We classified our research questions into two categories: general questions (GQ) and specific questions (SQ). The first category (GQ) points out the current state-of-the-art, draws a taxonomy, and describes the main areas of application. The general questions concern a broader view of IPA, pinpointing promising research directions for further investigation. The second category (SQ) explores some derived specific research questions to improve the study filtering process, which pinpoints questions surrounding the domains, privacy and security, architecture, characteristics, and application areas of the considered corpus.

2.3. Sources of information

The current study selected an appropriate set of databases to get extensive and broad coverage of the literature and increase the

Table 1
General and specific research questions.

Identifier	Research question
General questions (GQ)	
GQ1	What is the current state-of-the-art for IPA?
GQ2	How would be a taxonomy for IPA classification?
GQ3	What are the areas that provide opportunities to IPA applications?
Specific questions (SQ)	
SQ1	What is the current personal assistants' usage?
SQ2	Are there privacy, security or usage problems with the assistants?
SQ3	What are the architectures of IPA?
SQ4	How advanced are non-commercial IPA solutions?
SQ5	What are the main characteristics of commercial IPA solutions?
SQ6	What are the main subjects related to IPA?

probability of finding highly relevant articles. Therefore, the search covered the following electronic source databases:

- ACM Digital Library[5]
- IEEE eXplore[6]
- ScienceDirect[7]
- Springer[8]
- Scopus[9]

2.4. Additional sources

Besides the current sources of information, the search covered some additional sources:

- Reference lists from primary studies and other review articles;
- Books and technical reports.

2.5. Search criteria

The main aim of search criteria is to identify recent advances on Intelligent Personal Assistants. Also, past literature reviews were used to understand the context, keywords and key references. Besides this, we used Petticrew and Roberts (2006) *Population, Intervention, Comparison, Outcome, and Context* (PICOC) criteria as guidelines to define research string.

The PICOC criteria were defined based on general research questions pinpoint to answer the specific research questions with a limited focus. Therefore, the criteria were defined as follows.

2.5.1. Population

The populations involve keywords, related terms and some variants with the same meaning for the technologies and standards on IPA. Therefore, we defined the proposed search string in subsection search scope for the selection.

2.5.2. Intervention

Once the intervention is about the context of search (Petticrew & Roberts, 2006), we used the following terms to filter studies in line with the purposes: intelligent personal assistant and intelligent personal attendant.

2.5.3. Comparison

The comparison considers different architectures, types, privacy statements, usability and kind of solution (open or closed-solution) of IPA.

2.5.4. Outcome

This step determines which outcomes are the most relevant for answering the research question (Petticrew & Roberts, 2006). Therefore, we state as outcomes the knowledge of IPA solutions, besides their user privacy statement, usability, domains of applicability used to promote the automation of tasks or user's interests.

2.5.5. Context

We analyzed the context of IPA information coverage regarding content such as usability, domains of applicability, information grouping, security and privacy in the user's tasks or interests.

2.6. Search scope

The search scope used to obtain source studies from selected electronic databases made use of the constructed research keywords. Hence, the query searched for works published after 2012 and that contain the following words in the abstract: *"intelligent personal assistant" OR "intelligent personal attendant" OR "automated personal assistant" OR "automated personal attendant" OR "personal assistant" OR "personal attendant"*.

We undertook a document search to ensure the completeness of our study. Even so, some known research articles were not included in the predefined search strategy due to many reasons, like different article title, search string, keywords not in the abstract, and others.

2.7. Inclusion and exclusion criteria

After studies obtaining, we started the inclusion and exclusion criteria to filter the works that were not relevant and kept those that were the most representative. To that, we used the terms of population and intervention criteria as follows:

- Exclusion criteria 1: the article does not address IPA or related acronyms (population criteria);
- Exclusion criteria 2: the article does not address "personal assistant" or "personal attendant" and their plurals (intervention criteria).

In the first stage (1), according to Roehrs et al. (2017), we removed the impurities from the search results. As impurities, we mean the names of conferences correlated to the search keywords that were in the search results because of the characteristics of the different electronic databases. Then in stage (2), we filtered the articles by title and abstract because some studies did not address IPA as a subject. In the next step (3), we grouped all the remaining studies and then removed the duplicates automatically based on titles and authors. This step is important because some studies were in more than one database. At the final stage (4), we filtered by full text because some studies remained that were not mainly related to this review.

[5] www.acm.org/dl.
[6] ieeexplore.ieee.org.
[7] www.sciencedirect.com.
[8] www.springerlink.com.
[9] www.scopus.com.

Table 2
The set of proposed questions for full-text filtering proposed by Roehrs et al. (2017).

Identifier	Full-text question
C1	Does the article clearly show the purpose of the research?
C2	Does the article adequately describe the literature review, background, or context?
C3	Does the article present the related work concerning the main contribution?
C4	Does the article have an architecture proposal or research methodology described?
C5	Does the article have research results?
C6	Does the article present a conclusion related to the research objectives?
C7	Does the article recommend future works, improvements, or further studies?

In our case, the number of irrelevant articles is high as research articles on Intelligent Personal Assistants are hard to distinguish from Conversational Agents. Also, there are many Conversational Agents which overlap with intelligent personal assistants. Studies were eligible for inclusion in the review if their focus of the study was IPA in general. We included studies, software or architecture of both students and professional for IPA. The systematic review also included qualitative and quantitative research studies, published starting from 2012 to make the search query comprehensive. Only studies written in English or Brazilian Portuguese were accepted. We included technical reports in our study.

2.8. Quality assessment

After using the inclusion and exclusion criteria to select relevant articles that contain Intelligent Personal Assistants research, we performed a quality assessment of the remaining articles. We used as criteria to evaluate the selected articles the purpose of research, contextualization, literature review, related work, and methodology besides the conclusion and results. To reduce the empirical barriers of full-text filtering, we used a set of questions listed in Table 2 proposed by Roehrs et al. (2017) that validate if the selected articles met the quality criteria are listed.

3. Results

In this section, we present the results obtained from the collection of articles from five databases related to the research topic. We aim to answer the proposed research questions in Table 1, besides proposing an updated taxonomy and vision about the main challenges of IPAs. Following, we describe all the steps taken and the results obtained.

3.1. Performing article selection

We summarized the selection and filtering process in Fig. 1. As shown, our search returned over 3.472 total articles, which became 881 (74.6%) after impurities removal. Following, they were narrowed down to 397 (54.9%) documents after filter by title and abstract, which title filter was done through keyword match, and the abstract filter through a quick read looking for inclusion and exclusion criteria described in the "Inclusion and exclusion criteria" subsection. Then, the articles were grouped, and those identified as duplicates were removed, remaining 96 (75.8%). At the end of the filtering process, we identified that some articles were not particularly related to this survey, so we read they entirely to select a final list of 58 (38.5%) articles based on the inclusion and exclusion criteria.

To better represent the Intelligent Personal Assistants study domain, we classified each article found according to the area and type of work. The final list of selected articles with their classification is seen in Table 3.

3.2. Data extraction and answers to the research questions

In this subsection we present the answers for our proposed research questions.

3.2.1. GQ1 - What is the current state-of-the-art for IPA?

To better represent our systematic review findings and answer GQ1 - What is the current state-of-the-art for IPA? - we propose the Fig. 2, which shows that the majority of works are in general computing, infrastructure, and usability domains. On the other hand, the highlighted domains have more articles than other areas. We can see Health in the top three mean of citations per work: Infrastructure (16.25%), Health (11.83%), and General (8.21%).

As we can see in Fig. 3, the minor cited domains seem to be unchangeable on the last five years, which could be caused by some works particularity or specificity. However, there was a rise on general (32.16%) with focus on IPA solutions (17.86%), on usability (22.41%), on the analysis of published IPA solutions (10.71%), and Infrastructure (13.79%), mainly covering architectures of solutions (25%). Other domains such as education, health, and privacy seem to carry a broad set of focuses that are unexplored yet. Researches with education approach presented just 1 work per target, as follow: second language (Dizon, 2017), recommender systems(Duque Méndez, Rodríguez Marín, & Ovalle Carranza, 2018), the proposal of an architecture (Swartout et al., 2016), student assistance (Todorov, Stoyanov, Valkanov, Daskalov, & Popchev, 2016) and machinery maintenance (Zhu et al., 2014). Works focusing on health area are distributed as 1 article targeting autism (Allen, Shane, & Schlosser, 2018), 2 for elderly people (Angelini et al., 2013; Hornos et al., 2018), 1 for surgeons (Jalaliniya & Pederson, 2015), 1 for mobile gateway (Santos et al., 2016) and

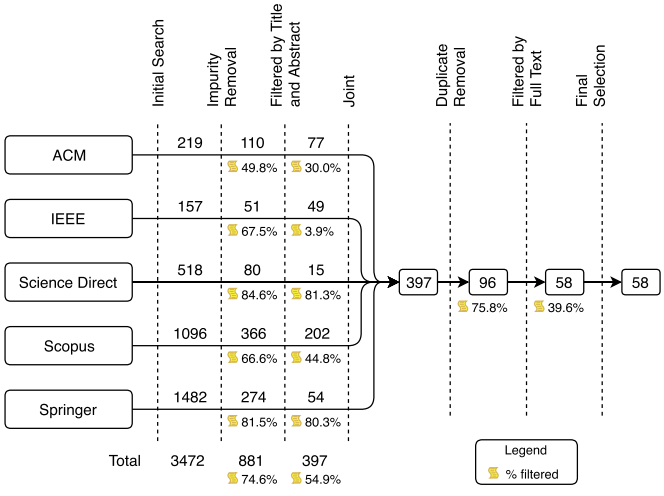
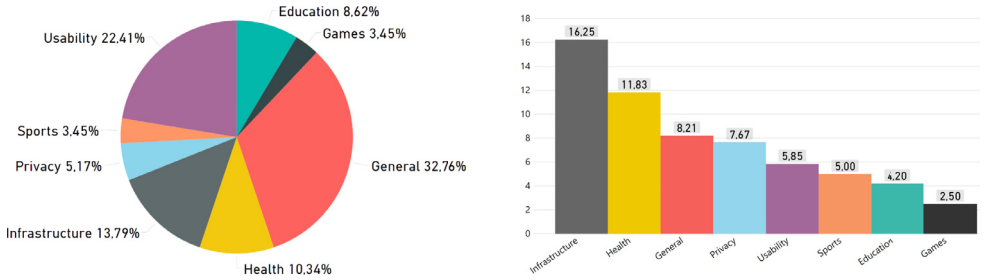


Fig. 1. Systematic mapping study–article selection.



(a) Works by area (b) Average citation by area

Fig. 2. Analysis of articles application area.

Table 3
The final list of selected articles with their classification.

Index	Article	Area	Type of work	Target	Citations
1	Allen et al. (2018)	Health	Tool	Autism	1
2	Angelini et al. (2013)	Health	Tool	Elderly people	30
3	Azaria and Hong (2016)	General	Review	Recommender Systems	12
4	Bahreinian and Crestani (2017)	General	Technique improvement	Meetings	4
5	Bellegarda (2013)	General	Study	IPA	9
6	Bellegarda (2014)	General	Study	IPA	69
7	Carvajal et al. (2018)	General	Technique improvement	Natural Language Interface	0
8	Chihani et al. (2013)	General	Framework	User empowerment	0
9	Cicció and Quesada (2018)	Games	Framework	Audio games	1
10	Costa et al. (2018)	Usability	Review	Elderly people	0
11	Cowan et al. (2017)	Usability	Study	Infrequent user	4
12	Dizon (2017)	Education	Study	Second Language	0
13	Duque Méndez et al. (2018)	Education	Tool	Recommender Systems	1
14	Moorthy and Vu (2015)	Privacy	Study	Usability	15
15	Moorthy and Vu (2014)	Privacy	Study	Usability	8
16	Ehrenbrink et al. (2017)	Usability	Study	IPA	0
17	Graus et al. (2016)	Usability	Study	IPA	5
18	Hauswald et al. (2016)	Infrastructure	Study	Architecture	5
19	Hauswald et al. (2015)	Infrastructure	Study	Optimization	92
20	Heras et al. (2018)	Usability	Study	Ambient Assisted Living	0
21	Hsieh and Buehrer (2014)	Usability	Tool	Usability	0
22	Heredero et al. (2013)	Infrastructure	Framework	Architecture	1
23	Hornos et al. (2018)	Health	Tool	Elderly people	1
24	Jalaliniya and Pederson (2015)	Health	Tool	Surgeons	10
25	Kennington and Shukla (2017)	General	Study	IPA autonomous learning	0
26	Kiseleva et al. (2016b)	Usability	Study	IPA	23
27	Kobayashi et al. (2015)	Games	Study	Spoken dialog systems	4
28	Lee, Lee, Kim, and Lee (2015)	General	Technique improvement	Dialog Act	0
29	Lopatovska and Williams (2018)	Usability	Study	Personification	0
30	López et al. (2018)	General	Study	Usability	4
31	Meurisch, Ionescu, Schmidt, and Mühlhäuser (2017)	General	Study	Proactivity	0
32	Milhorat et al. (2014)	General	Technique improvement	Architecture	15
33	Misra and Such (2017)	General	Study	IPA	0
34	Moore (2016)	General	Study	IPA	8
35	Nogueira et al. (2017)	Privacy	Study	IPA	0
36	Oishi and Fukuta (2016)	General	Tool	Architecture	3
37	Orehovački et al. (2018)	General	Study	Quality	0
38	Ponciano et al. (2015)	Usability	Technique improvement	User behavior	2
39	Popovic et al. (2015)	Usability	Technique improvement	Language	2
40	Porcheron et al. (2017)	Usability	Study	Collocated Interactions	7
41	Pozna et al. (2013)	General	Tool	Architecture	4
42	Ricky and Gulo (2015)	General	Review	Architecture	1
43	Saad et al. (2017)	Usability	Study	Usability	3
44	Santos et al. (2016)	Health	Study	Mobile gateway	29
45	Sarikaya (2017)	General	Review	Architecture	9
46	Silva et al. (2017)	Health	Study	Clinical Practice Guidelines	0
47	Sörös et al. (2013)	Sports	Study	Bike collaborative training	10
48	Strayer et al. (2017)	General	Study	Cognitive workload	27
49	Sun et al. (2016)	General	Technique improvement	Intent tracking	11
50	Sun et al. (2017)	General	Technique improvement	Intent prediction	3
51	Swartout et al. (2016)	Education	Study	Architecture	3
52	Todorov et al. (2016)	Education	Study	Student assistance	3
53	Tur, Deoras, and Hakkani-Tür (2014)	General	Study	Conversational understanding	9
54	Zhu et al. (2014)	Education	Tool	Machinery Maintenance	14
55	Vinothini et al. (2017)	General	Study	IPA	0
56	Vora et al. (2017)	Sports	Study	IPA	0
57	Yorke-Smith et al. (2012)	Usability	Framework	Office Task Management	30
58	Yee and Juan (2017)	General	Study	Disabled people	0

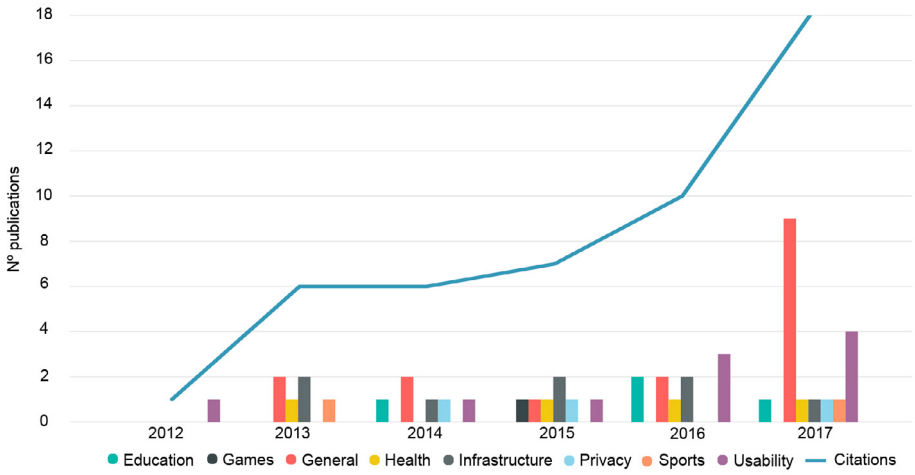


Fig. 3. Analysis of articles domains over the years by citations.

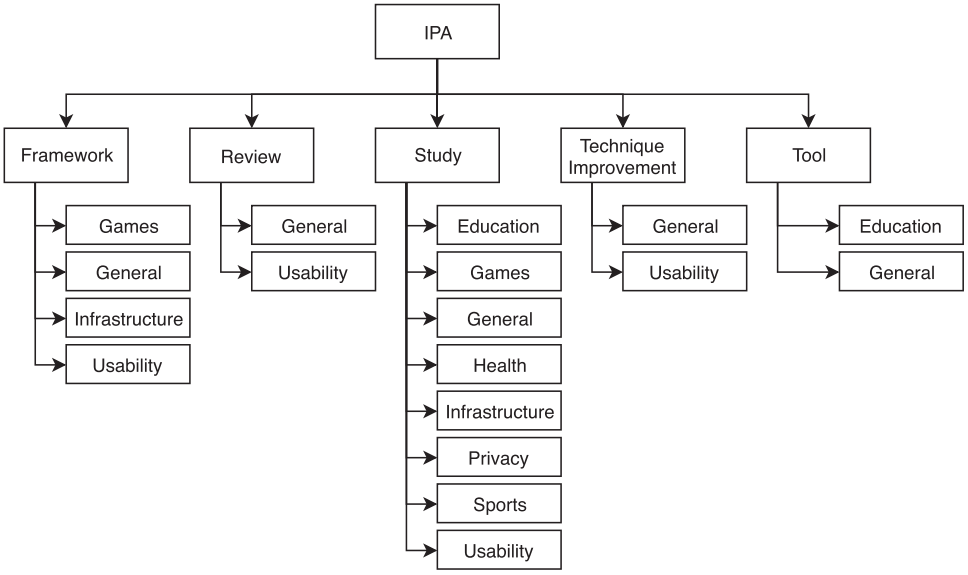


Fig. 4. Intelligent Personal Assistant taxonomy based on the considered related articles. The taxonomy presents an overview of possible alternatives in terms of aims, content, and architecture.

Table 4
The summary table of voice-activated articles and their platforms.

Filter		Articles
voice-activated		Allen et al. (2018), Cicció and Quesada (2018), Cowan et al. (2017), Dizon (2017), Moorthy and Vu (2015, 2014), Ehrenbrink et al. (2017), Hauswald et al. (2016, 2015), Hsieh and Buehrer (2014), Heredero et al. (2013), Jalaliniya and Pederson (2015), Kiseleva et al. (2016b), Kobayashi et al. (2015), Lopatovska and Williams (2018), López et al. (2018), Porcheron et al. (2017), Strayer et al. (2017), Todorov et al. (2016), Tur et al. (2014), Zhu et al. (2014)
proactive		Jalaliniya and Pederson (2015), Todorov et al. (2016)
Platform	wearable	Angelini et al. (2013), Heredero et al. (2013), Hsieh and Buehrer (2014), Jalaliniya and Pederson (2015), Allen et al. (2018), Cicció and Quesada (2018)
	mobile	Kobayashi et al. (2015), Popovic et al. (2015), Santos et al. (2016), Todorov et al. (2016)
	desktop	Zhu et al. (2014), Oishi and Fukuta (2016)
	web	Kennington and Shukla (2017), Duque Méndez et al. (2018), Hornos et al. (2018)
	others	Hauswald et al. (2016), Hauswald et al. (2015), Hsieh and Buehrer (2014)

1 for clinical practice guidelines (Silva, Oliveira, Neves, Satoh, & Novais, 2017). On the privacy domain, we identified two works focusing on usability (Moorthy & Vu, 2014; 2015) and one on IPA (Nogueira, Maciel, Viterbo, & Vecchiato, 2017).

Table 4 shows another perspective of view that only 51.72% of final articles used an IPA. In which, 51.14% are voice-activated, 48.57% have any personalization of applications for wearable, mobile, desktop, web or others and only 10.81% used an IPA that is proactive with the user. These works are almost all a custom developed IPA tool applied to health or education domains with applications for the assistance of elderly (Hornos et al., 2018), surgeons (Jalaliniya & Pederson, 2015), students (Todorov et al., 2016),

Table 5
The articles classification through the proposed taxonomy.

Type of work	Area	Articles
Framework	Games	Cicció and Quesada (2018)
	General	Chihani et al. (2013)
	Infrastructure	Heredero et al. (2013)
	Usability	Yorke-Smith et al. (2012)
Review	General	Ricky and Gulo (2015), Azaria and Hong (2016), Sarikaya (2017)
	Usability	Costa et al. (2018)
Study	Education	Swartout et al. (2016), Todorov et al. (2016), Dizon (2017)
	Games	Kobayashi et al. (2015)
	General	Bellegarda (2013), Bellegarda (2014), Tur et al. (2014), Kennington and Shukla (2017), Meurisch et al. (2017), Misra and Such (2017), Moore (2016), Strayer et al. (2017), Vinothini et al. (2017), Yee and Juan (2017), López et al. (2018), Orehovački et al. (2018)
	Health	Santos et al. (2016), Silva et al. (2017)
	Infrastructure	Hauswald et al. (2015), Hauswald et al. (2016)
	Privacy	Moorthy and Vu (2014), Moorthy and Vu (2015), Nogueira et al. (2017)
	Sports	Sörös et al. (2013), Vora et al. (2017)
	Usability	Graus et al. (2016), Kiseleva et al. (2016b), Cowan et al. (2017), Ehrenbrink et al. (2017), Porcheron et al. (2017), Saad et al. (2017), Heras et al. (2018), Lopatovska and Williams (2018)
Technique improvement	General	Milhorat et al. (2014), Lee et al. (2015), Sun et al. (2016), Bahreinian and Crestani (2017), Sun et al. (2017), Carvajal et al. (2018)
	Usability	Ponciano et al. (2015), Popovic et al. (2015)
Tool	Education	Zhu et al. (2014), Duque Méndez et al. (2018)
	General	Oishi and Fukuta (2016)

and employees (Zhu et al., 2014). Therefore, these findings seem to appoint a gap in proactive IPA solutions as well as cited domains as another.

The works that did not use IPA focused more on developing studies about the assistant technologies (Bellegarda, 2013; 2014; Graus, Bennett, White, & Horvitz, 2016; Moore, 2016; Nogueira et al., 2017; Vinothini, Shanmugapriya, Sharmathi, & Subashini, 2017; Vora, Bekaroo, Santokhee, Juddoo, & Roopowa, 2017) and performing studies (Swartout et al., 2016), reviews (Ricky & Gulo, 2015; Sarikaya, 2017), improvements (Milhorat et al., 2014) and tools (Pozna, Foldesi, & Kovacs, 2013) about their architectures. Also, there were some proposed improvements for natural language interfaces (Carvajal, Quesada, López, & Brenes, 2018), intents handling (Sun et al., 2016; Sun, Yuan, Xie, McDonald, & Zhang, 2017), and architectures (Milhorat et al., 2014). Despite the current rise of IPA technologies, the literature (Cowan et al., 2017; Dubiel, Halvey, & Azzopardi, 2018; Han & Yang, 2018; Lee & Kwon, 2013; Saad, Afzal, El-Issawi, & Eid, 2017) describes a gap of more human-friendly interfaces and natural dialogs of IPAs. Thus, corroborating with Ricky and Gulo (2015) statements that the state-of-the-art still without a default method for creating the assistants.

3.2.2. GQ2 - How would be a taxonomy for IPA classification?

After analyzing a series of studies, we investigated some current addressed issues in the IPA field. Therefore, we managed to build the proposed taxonomy (Fig. 4) by analyzing the selected articles and seeking to answer this general research question. The main aim of taxonomy is to gather and organize the Intelligent Personal Assistants area based on essential characteristics of the models, and we believe that this taxonomy could help to classify, compare, and evaluate different IPA types and domains. Moreover, to better represent the Intelligent Personal Assistants study domain, we classified each article found according to the area, type of work, year, citations, IPA platform, IPA device, and proactivity. This classification can provide an overview of possible alternatives regarding aims, content, and architectures in Fig. 4.

Table 5 summarizes surveyed works and their classifications according to the proposed taxonomy in Fig. 4. We classified each article in five main groups according to their type of work: framework, review, study, technique improvement, and tool. The first category holds articles that proposed a framework to develop or extend personal assistants or their new features, while the second addresses works that review the literature through a survey or a systematic review of IPA. The third group contains the articles that proposed studies or advances in IPA or promoted a better understanding of them. The articles on the fourth category address the recent advances in IPA techniques or new approaches for IPA technologies. Finally, category five holds articles that proposed new tools that to develop, extend or assist personal assistants applications.

After the classification by the type of work, we classified each article in a second category according to their area of application such as education, games, general, health, infrastructure, privacy, sports, and usability. In order to reduce the classification bias, each author votes the classification of each article. Finally, the most voted classifications for each article was selected. The summarized article classification is shown in Table 5 and the complete list of works and their classifications are shown in Table 3.

3.2.3. GQ3 - What are the areas that provide opportunities to IPA applications?

We have identified opportunities areas to IPA applications based on their citing counting. In this sense, the articles classified on the educational area lead to learning a second language (Dizon, 2017) and provide student assistance (Todorov et al., 2016; Zhu et al., 2014), while the games and sports areas focus on user adherence (Kobayashi, Tanio, & Sassano, 2015), develop a framework for audio games (Cicció & Quesada, 2018) and outdoor sports like fishing (Vora et al., 2017) and biking (Sörös et al., 2013). As expected by the health area, the most cited works focus on storing and processing user vital signs (Angelini et al., 2013; Santos et al., 2016) and suggest therapies (Allen et al., 2018; Silva et al., 2017). The same occurs in the privacy and usability domain, where most of the works focus on improving user interactions (Kiseleva et al., 2016b), understanding how people use IPA (Cowan et al., 2017; Graus et al., 2016; Hsieh & Buehrer, 2014; Porcheron, Fischer, & Sharples, 2017) and explaining their uses (Moorthy & Vu, 2014; 2015; Nogueira et al., 2017). The works in the infrastructure area focus on optimization of the assistant and their dialog (Hauswald et al., 2016; 2015; Heredero, Penmetsa, Agrawal, & Shastri, 2013). The general studies have many focuses about the IPA, which we could highlight the understanding (Bellegarda, 2013; 2014; Moore, 2016) and new assistants proposes (Misra & Such, 2017; Vinothini et al., 2017) articles.

Table 6
Privacy comparison between commercial personal assistants based on Nogueira et al. (2017).

	Siri	Cortana	Google Assistant
Platform	iOS	Windows	iOS, Android
Proactive	No	Yes	Yes
Partial control of collected data	No	Yes	No
Storage	Cloud	Cloud	Cloud
Data source	Web services	Bing	Google
Access to personal data	During the use	Always	Always
Collection of voice inputs	Yes	Yes	Yes
Access to device data	No	No	Yes
Communication on behalf of the user	No	Yes	No

3.2.4. SQ1 - What is the current personal assistants' usage?

A broad set of surveyed articles (Cowan et al., 2017; Dubiel et al., 2018; Moorthy & Vu, 2014; 2015; Shneiderman, 2000) describes that the contextual social issues play an important role in speech conversational interfaces. Some of them (Han & Yang, 2018; Moorthy & Vu, 2014; 2015) showed that people are more likely to use their IPAs in private locations to transmit non-private information. Besides likely to use a smartphone keyboard instead an IPA to transmit information because they think that interaction with a voice agent in public-spaces to get non-private information could be socially unacceptable. A more recent study (Dubiel et al., 2018) also supports this information. According to the author, the usage frequency does not imply less concern about data privacy when using IPAs. Cowan et al. (2017) found that users become frustrated when they were asked by the assistant to engage visually with the screen or to confirm or select options by taping the touchscreen rather than through using speech.

Most of the users currently use their IPAs for simple tasks such as searches, weather, and music. Other works (Cowan et al., 2017; Dubiel et al., 2018) support that frequent users were significantly more satisfied with their IPAs overall, which the authors suggest a potential link between user satisfaction and IPA usage frequency. Also, although both frequent and infrequent IPA users have similar perceptions and expectations regarding their assistants, the speech recognition is one of the main concerns of infrequent users of IPAs (Dubiel et al., 2018).

3.2.5. SQ2 - Are there privacy, security or usage problems with the assistants?

Contrary to our expectations, there are only a few studies on the privacy domain. A comparative study of data privacy was made in Table 6. As seen on Nogueira et al. (2017), about 81.8% of users agree that the current methods would be less invasive if there were some legislation that protected the privacy of shared data, and also would consider the methods less invasive if it were possible to have more accurate control of the shared information. The three analyzed IPAs used a cloud environment to store data and services on the web as data sources for answering questions. As these features run over the Internet, is mandatory the use of a secure protocol as HTTPS. Another security issue is related to access to the user's personal data. All studied platforms are granted to read user data, but the user is generally not aware of what kind of data the application is consuming.

Another study (Alepis & Patsakis, 2017) showed that Siri, Cortana, Google Assistant, and Alexa have vulnerabilities on voice activation and one can easily control and manipulate the voice commands remotely, issuing arbitrary commands which can significantly expose the users. As showed by Alepis and Patsakis (2017), the compromised device could be used to further exploit victims, by attacking other devices in proximity, regardless of whether his malicious application infects them. According to the authors, attackers could have an advantage because the arbitrary voice command originates from another device, then the voice cancellation mechanisms cannot be applied.

Recently, the four major commercial IPAs - Alexa, Cortana, Google Assistant, and Siri - provided a voice recognition feature that identifies the users by analyzing their voices. It is similar to a fingerprint, but using the user's voice as input. This feature enhances significantly the application security, allowing multiple users sharing the same device, preserving the data privacy for every individual user. When taking the IPA device and interaction in account, Strayer, Cooper, Turrill, Coleman, and Hopman (2017) suggest caution in introducing IPA interactions in the vehicle because of the surprisingly high levels of the workload associated, which could cause distractions and can lead accidents.

3.2.6. SQ3 - What are the architectures of IPA?

The relevance of a robust architecture for IPA is trending, and there are several IPA architectures proposals in last years (Hauswald et al., 2016; 2015; Heredero et al., 2013; Sarikaya, 2017; Zambiasi & Rabelo, 2012). These authors appoint to the need of extendable assistant behaviors through skills, in order to provide both flexibility and scalability. Thus, the personal assistant behaviors make real use of the cloud computing concept, which is enabled through distributed web services over many repositories with application services provided by different companies, organizations or developers.

As shown by other work (Bellegarda, 2013), the major Intelligent Personal Assistants agents use the process described in Fig. 5. These agents have as the first step the transcription of speech on words or sentences to enable the use of Natural Language Understanding (NLU) tools and resources, leading to a semantic interpretation of the input.

In some cases, NLU engine catches noise (e.g., ambient sound) or misspelled words and can't interpret them itself, so dialog management cannot understand interaction context and need to start a user interaction thought questions to elicit the relevant information. On the other way, once the agent is successful in semantic interpretation, then it infers user intent and finds the best suitable action that corresponds to the intent. Finally, on the lasts steps, the agent selects the best outcome and return feedback to the user.

Some works found on this review proposed personal assistants architectures advances (Hsieh & Buehrer, 2014; Oishi & Fukuta, 2016; Pozna et al., 2013; Swartout et al., 2016), frameworks (Chihani, Bertin, & Crespi, 2013; Cicció & Quesada, 2018; Yorke-Smith, Saadati, Myers, & Morley, 2012), advances in techniques for predict user behavior (Ponciano, Pais, & Casal, 2015), approaches to perform a better intent tracking (Sun et al., 2016) and extend the assistant to other languages (Popovic, Pakoci, Jakovljevic, Kocis, & Pekar, 2015). Also, some articles proposed techniques to recommend the right information at the right time and helping IPAs to perform tasks (Bahreinian & Crestani, 2017), predict next user intent (Sun et al., 2017), and turn the conversation more user-friendly (Carvajal et al., 2018). In sequence, Milhorat et al. (2014) proposed a set of personal assistants

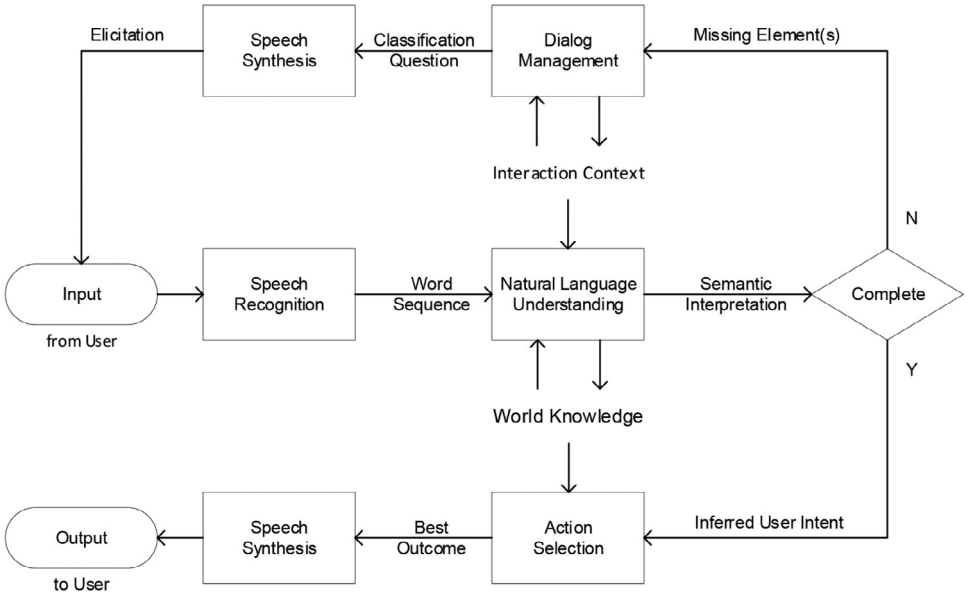


Fig. 5. An overview of the underlying interaction model of Intelligent Personal Assistant based on Bellegarda (2013).

Table 7
Custom developed IPA solutions.

	Name	Platform	Speech interaction	Visual interaction	Gesture interaction	Proactive
Hornos et al. (2018)	VIRTRAEL	Web	No	Yes	No	Yes
Misra and Such (2017)	PACMAN	Web	No	No	No	No
Santos et al. (2016)	AMBRO	Smartphone	Yes	Yes	No	No
Swartout et al. (2016)	PAL3	Undetermined	No	Yes	No	No
Todorov et al. (2016)	LISSA	Smartphone	Yes	Yes	No	Yes
Vinothini et al. (2017)	XIU	Cars	Yes	No	No	No
Vora et al. (2017)	JarPI	Raspberry Pi	Yes	No	No	No
Yee and Juan (2017)	PAL	Raspberry Pi	Yes	Yes	No	No
Zhu et al. (2014)	AR-Mentor	Own glass	Yes	Yes	Yes	Yes

challenges that could improve their current state-of-the-art architecture thought the improvement of IPA context-awareness using the vast amount of data available and not only depending on what is directly requested by the user. These challenges already were overcome by some commercial personal assistants applications, including Google Assistant (Table 6), but they cause a user privacy issue due to the needing of storing much information as real-time localization, speech, and others.

The majority of surveyed works that aim to propose architectures used an already known platform named *Sirius* (Hauswald et al., 2015), which is "an open end-to-end IPA web-service application that accepts queries in the form of voice and images, and responds with natural language" (Hauswald et al., 2015, p. 1). Sirius is composed of three services: automatic speech recognition, question answering, and image matching. The first one uses a combination of a Hidden Markov Model and Gaussian Mixture Model (Povey et al., 2011) (GMM) or a Deep Neural Network (DNN) (Rybach et al., 2011). On the second service, the text output from automatic speech recognition is used as input to OpenEphyra (Seide, Li, & Yu, 2011). Finally, they based the image matching service on the SURF algorithm (Bay, Tuytelaars, & Van Gool, 2006).

3.2.7. SQ4 - How advanced are non-commercial IPA solutions?

The aim of this question is to identify noncommercial IPA initiatives, its maturity level and what kind of application they are proposing to run. We found 9 works that proposed a new Intelligent Personal Assistant solution, presented in Table 7. There are 33.3% works applied to the General area. The research developed by Misra and Such (2017) is a textual interaction on a web platform and has no speech interface. Vinothini et al. (2017) have a speech interface to run on car systems. Yee and Juan (2017) works with speech and visual interfaces and was developed to run on a Raspberry Pi.

Types of researche focusing on the Education area are also covered by 33.3% of the articles. Swartout et al. (2016) proposed an architecture to provide visual interaction to IPA, Todorov et al. (2016) presented an IPA for students assistance with speech and visual interaction and (Zhu et al., 2014) proposed a speech, visual and gesture interaction IPA running on a customized glass for machine maintenance applications.

Studies in Health domains summarize 22.2%. Hornos et al. (2018) proposed a web tool for visual interaction for elder people. Visual and speech interfaces were developed by Santos et al. (2016) to users interact throughout a smartphone. On the Sports area, only one study was presented by Vora et al. (2017) offering a speech interaction on the Raspberry Pi platform.

Aggregating the studies by interaction mode, we found 66.7% of them using voice interface, 66.7% with visual interface and only 11.1% capturing gestures. Regarding the Platform in which the IPA was executed, web, smartphones and Raspberry Pi account 22.2% each. Customized glass and cars were used by 11.1% of works. Only one study did not identify the platform.

3.2.8. SQ5 - What are the main characteristics of commercial IPA solutions?

The question SQ5 was formulated to draw a profile of commercial IPA solutions. We found 17 works that studied applications or

Table 8
Commercial IPA solutions.

Articles	Amazon	Apple	Google	Microsoft	Others	Platform
Allen et al. (2018)	Yes	No	No	No	No	Echo
Cicció and Quesada (2018)	Yes	No	No	No	No	Echo
Cowan et al. (2017)	No	Yes	No	No	No	Smartphone
Dizon (2017)	Yes	No	No	No	No	Echo
Ehrenbrink et al. (2017)	No	Yes	Yes	Yes	No	Smartphone
Graus et al. (2016)	No	No	No	Yes	No	Undetermined
Jalaliniya and Pederson (2015)	No	No	Yes	No	No	Google glass
Kiseleva et al. (2016b)	No	No	No	Yes	No	Smartphone
Kobayashi et al. (2015)	No	Yes	No	No	No	Smartphone
Lopatovska and Williams (2018)	Yes	No	No	No	No	Echo
López et al. (2018)	Yes	Yes	Yes	Yes	No	Smartphone
Moorthy and Vu (2015)	No	Yes	Yes	No	Yes	Smartphone
Nogueira et al. (2017)	No	Yes	Yes	Yes	No	Smartphone
Orehovački et al. (2018)	No	No	Yes	No	Yes	Smartphone
Sörös et al. (2013)	No	No	Yes	No	No	Google glass
Strayer et al. (2017)	No	Yes	Yes	Yes	No	Smartphone
Tur et al. (2014)	No	No	No	Yes	No	Undetermined

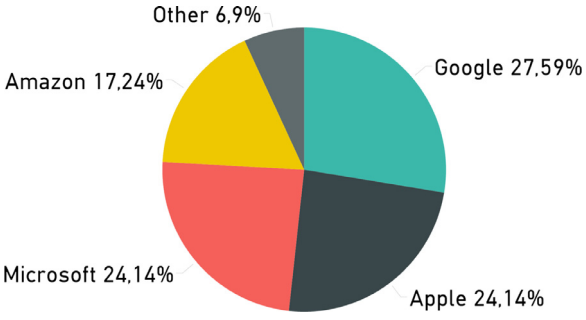


Fig. 6. Articles focusing on commercial IPAs.

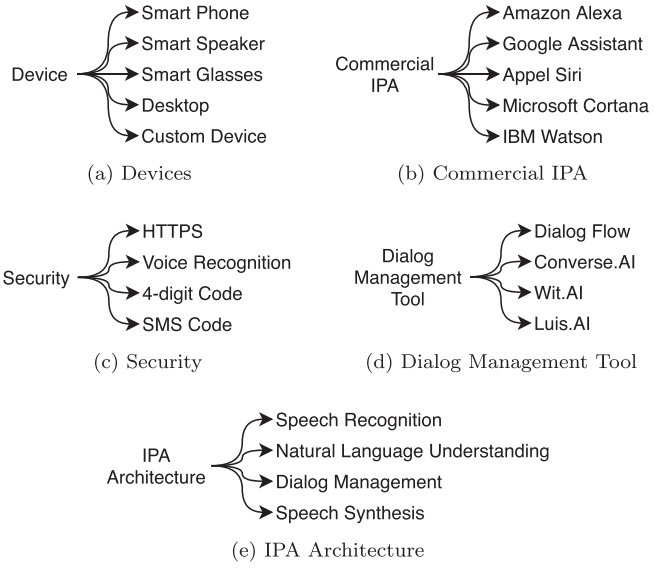


Fig. 7. Summary of articles application area.

characteristics of commercial platforms, listed in Table 8. The number of works found in this research grouped by IPA's owner can be seen in Fig. 6. In this graph, we can see a balance among works using Google platform (27.6%), Apple (24.1%) and Microsoft (24.1%). Amazon is slightly lower, reaching 17.2% of studies. Other platforms were used by 6.9% of works.

Regarding the application area, General and Usability compound 29.4% of works each. López, Quesada, and Guerrero (2018) made a comparative study of major commercial platforms, evaluating the naturalness, emotion expressions, tone and pace of the assistant's voice. He also evaluated visual interaction. Moore (2016) and Orehovački, Babić, and Etinger (2018) approached the gap caused by the mismatch between the capabilities and expectations of human users and the features of IPA application. Usability of IPA on smartphones was studied by Cowan et al. (2017), Ehrenbrink, Osman, and Möller (2017) and Kiseleva et al. (2016b).

The use of personal assistants in Games was found in 11.8% of works. Even games have a strong graphical and sound appeal, the major focus is on music and sound effects, not in a voice input interface. In this sense, Cicció and Quesada (2018) used Alexa to help visually impaired people to play games. Kobayashi et al. (2015) also proposed voice commands through Siri to increase the human interaction between players over a network. On the Health domain, Allen et al. (2018) used Google Echo to interact with children with autism. To aid orthopedic surgeons, Jalaliniya and Pederson (2015) proposed an application running on Google Glass. On Privacy domain, Nogueira et al. (2017) proposed an architecture to protect the user data stored, accessed and transmitted by Apple, Google and Microsoft platforms (Sörös et al., 2013) used Google Glass to develop a bike collaborative training application.

3.2.9. SQ6 - What are the main subjects related to IPA?

Compiling all articles studied in this article, we developed Fig. 7, that is a summary of five classification subjects. Part (a) depicts the devices found in the studies. Smart Phones and Desktops are the most frequently used devices due to its simplicity and availability. Smart Speakers come next, and Smart Glasses were the less used devices due to their specificity. Custom Devices are equipment developed or assembled specifically for a given scenario. Part (b) illustrate Commercial IPA solutions, divided in Amazon Alexa, Google Assistant, Apple Siri, Microsft Cortana, and IBM Watson. Because they are market-standard solutions, with extensive documentation and API access, they have appeared in several studies.

Fig. 7(c) addresses security issues. As all commercial IPA run on a Cloud platform using the Internet, the protocol to communicate between the device and the IPA is the well-known HTTPS. To identify the user, IPA presents a feature to analyze and recognize the user's voice according to several audio processing techniques. It works as a voice-fingerprint, uniquely identifying the user, adding high-level reliability to the platform. Parallel to voice recognition, a spoken 4-digit code or an SMS code can be used

as an authentication or authorization token. Dialog Management Tools are presented in part (d). They are responsible for managing the state and the flow of conversation. The main tools identified in the research are Dialog Flow, Converse AI, Wit AI, and Luis AI. Fig. 7(e) lists the main modules of an IPA Architecture. Speech Recognition is responsible for understanding the user utterances and convert the speech to text. Natural Language Understanding uses Artificial Intelligence to build a model and classify the words and sentences in semantic structures, identifying the user's intents. Dialog Management module organizes the dialog with the user, answering questions and asking for missing information. Last, Speech Synthesis makes the conversion of the sentence provided by Dialog Management module in text format to audio format, allowing the user to hear the sentence.

4. Limitations

In this article, we tried to mitigate the research bias and sought to answer the research questions in order to obtain an outline of the current literature related to Intelligent Personal Assistant without explicitly assessing any article that refers exclusively to the components improvement of IPA. Therefore, this research is limited to aspects related only to IPA rather than including new techniques for speech recognition or dialog management, for example. In this sense, the review focuses on works that addressing the IPA concepts and applications.

The research was limited to obtaining articles published in scientific portals presented in "sources of information" subsection that are related to Intelligent Personal Assistant domains and applications. Although the systematic review used the PICOC method (Petticrew & Roberts, 2006) and limited to studies found on these websites, and due to this, it may miss some relevant article from other portals.

The authors carried out the data extraction and discussed any disagreements before discard a work. In order to be extremely cautious in data extraction, the impurity, title, and abstract filters were made manually in our study. However, as appointed in other works (Rattan et al., 2013; Roehrs et al., 2017), manual searches may miss relevant articles.

5. Challenges and open questions

The review faced some challenges and open questions about intelligent personal assistants that could influence their use and bring them a new concept. The first one, as seen in Moorthy and Vu (2014), Moorthy and Vu (2015), Cowan et al. (2017), Nogueira et al. (2017) and Dubiel et al. (2018) there are issues related to usability, security, and privacy, which directly affect the technology confidence and adoption. The articles showed that most people use IPA only for simple tasks (e.g., music, weather, directions) that do not need any private information, which could cause a later adoption for assistants that request personal information to execute tasks. Among the reported issues, the privacy of IPA solutions and their security are big challenges that personal assistant applications will need to deal with (was stated in SQ1 subsubsection). There are many needs, even a more accurate control of the shared information through IPA, and other security barriers to protect users from malicious applications on their devices. Also, some technical efforts could promote new default operations and skills through tools or frameworks, in order to facilitate user customization and adoption. About the Internet of Things, there is an open question of how IPA will support and interact over wearable computing daily use.

One of the major issues is proactivity, in which theory of proactivity describes user desires and a model of helpfulness (Sarikaya, 2017; Schiaffino & Amandi, 2004). However, contrary to Maes (1994), this was not identified in our findings (SQ1 sub-subsection). Also, the personalization of the agents are a very important topic that was understudied. The literature Berry et al. (2017), Costa et al. (2018) and Heras, Palanca, and Chesñevar (2018) highlighted that the IPA must fit the users' profiles and learn their context (family and social) taking into account their emotional estates to resolve any potential request. Also, the IPA should be able to recognize users' goals, act proactively, and interact with other applications to accomplish them. Therefore, future research could deal with the proactivity and personalization challenges when developing intelligent personal assistants.

The IPA technology is still evolving in order to overcome the human-interaction barrier (Dubiel et al., 2018), which causes an increasing architecture advancement, and the amount of works citations explains it (Angelini et al., 2013; Jalaliniya & Pederson, 2015; Milhorat et al., 2014; Sun et al., 2016; Yorke-Smith et al., 2012; Zhu et al., 2014). Despite the rise of assistant technologies, we could not see any trending application target of IPAs. For instance, we found works proposing innovative approaches for audio games using IPAs (Cicció & Quesada, 2018), quality models for the assistants (Orehovački et al., 2018), and student's personal support to improve the learning process (Todorov et al., 2016). Also, we have not found any measure that enables the direct comparison of personal assistant applications. Hence, the comparison of the article in terms of applicability and performance is difficult and sometimes it was done empirically by the articles.

The literature analysis showed a big opportunity on targeting the elderly as primary IPA user profile (Costa et al., 2018). Most of the surveyed articles did not address a specific user profile (e.g., adult, younger, elderly) and then, not dealing with the usage differences. Targeting the elderly as default user could lead to new horizons in terms of personal and cognitive assistants for ambient assisted living. Meanwhile, the current research did not found any measure that enables the direct comparison of personal assistant applications. Hence, the comparison of the article in terms of applicability and performance is difficult and sometimes it was done empirically by the articles. Therefore, there are a lot of opportunities to propose strategies and methods to evaluate the IPA features (e.g., dialog flow, interaction quality, unknown dialog handling, response time, actions available, and integration with other applications).

There are other challenges around the IPA application domains. As stated in the GQ1 subsection, general computing, infrastructure, and usability domains have more articles than other areas, and therefore, are more explored. However, some domains such as education, health, and privacy also seem to carry a broad set of promising focuses that are unexplored yet (Bahreinian & Crestani, 2017; Duque Méndez et al., 2018). Applications on these areas could bring a new perspective to the IPA, like collect and monitor vital-signs, mental health applications, smart places, teaching, and more. Another important unexplored aspect is the use of questionnaires to obtain a more comprehensive understanding about the linguistics and the pedagogical ways to enhance language development (Dizon, 2017).

6. Conclusion

The current study proposed a systematic literature review to identify different critical areas of research on Intelligent Personal Assistants besides discussed their concepts, research methods, and significant findings. For this purpose, we performed a systematic analysis of the relevant articles in the last six years. We then propose a personal assistant's taxonomy that contains a set of domains and types of IPA. The taxonomy and review result made it possible to answer general and specify questions about the current

status, challenges, open issues, assistant usage, security, privacy, types, architectures, both custom and commercial IPA solutions.

Once we analyzed articles selected over the review, we noticed a broad set of findings and were able to identify some gaps, trending, and challenges regarding personal assistants. At first, we observe that IPA domains have much-unexplored focus. Another opportunity emerges in voice interactive IPA solutions on education and health domains. The analysis has shown that a few works proposed tools or frameworks for the assistant's and the majority focused on the assistant doing studies about their technologies and functionalities. We also noticed that some commercial personal assistant have vulnerabilities on voice activation, and one can easily control and manipulate the voice commands remotely. Furthermore, they may also cause a user privacy issue due to the need to store information, including real-time localization, speech, and others.

The final review analysis presents a set of findings and research items that can be used as a direction for future research by the scientific community. As a result, aside from only answering the research questions, we have also proposed contributions in the IPA field from the study of related work. To better elucidate them, we highlight:

- The mapping of current intelligent personal assistants usage and domains;
- A systematic review of the personal assistants;
- A taxonomy to classify the domains and characteristics of IPA applications.

Although were presented the contributions cited above, we also showed domains distributions besides their specific goals and a citation trending line over them. Therefore, as a result, we expect that the reader could be able to identify the taxonomy, besides trending domains, targets, and applications of intelligent personal assistants in academia.

In future studies, we envision a focus on the challenges and issues related to the study, especially on usability, security, and privacy, which directly affect the users' confidence in adopting an IPA. Other aspects that might come as a future study is to explore different domains of IPA usage besides proposing tools or frameworks to facilitate new assistants operations and skills. Also, future works could examine the models of architecture and the implementation of IPA following the expansion of the use of technologies such as wearable computing besides improving user experience taking on account usability, personalization, and user behaviors.

Declaration of Competing Interest

None.

Credit authorship contribution statement

Allan de Barcelos Silva: Writing - original draft, Conceptualization, Methodology, Investigation. **Marcio Miguel Gomes:** Writing - original draft, Conceptualization, Methodology, Investigation. **Cristiano André da Costa:** Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision. **Rodrigo da Rosa Righi:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Jorge Luis Victoria Barbosa:** Methodology, Investigation, Writing - review & editing. **Gustavo Pessin:** Methodology, Investigation, Writing - review & editing. **Geert De Doncker:** Writing - review & editing. **Gustavo Federizzi:** Writing - review & editing.

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