A systematic literature review on the usability of mobile applications for visually impaired users

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Interacting with mobile applications can often be challenging for people with visual impairments due to the poor usability of some mobile applications. The goal of this paper is to provide an overview of the developments on usability of mobile applications for people with visual impairments based on recent advances in research and application development. This overview is important to guide decision-making for researchers and provide a synthesis of available evidence and indicate in which direction it is worthwhile to prompt further research. We performed a systematic literature review on the usability of mobile applications for people with visual impairments. A deep analysis following the Preferred Reporting Items for SLRs and Meta-Analyses (PRISMA) guidelines was performed to produce a set of relevant papers in the field. We first identified 932 papers published within the last six years. After screening the papers and employing a snowballing technique, we identified 60 studies that were then classified into seven themes: accessibility, daily activities, assistive devices, navigation, screen division layout, and audio guidance. The studies were then analyzed to answer the proposed research questions in order to illustrate the different trends, themes, and evaluation results of various mobile applications developed in the last six years. Using this overview as a foundation, future directions for research in the field of usability for the visually impaired (UVI) are highlighted.

A Systematic Literature Review on the Usability of Mobile Applications for Visually Impaired Users

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Abstract

Interacting with mobile applications can often be challenging for people with visual impairments due to the poor usability of some mobile applications. The goal of this paper is to provide an overview of the developments on usability of mobile applications for people with visual impairments based on recent advances in research and application development. This overview is important to guide decision-making for researchers and provide a synthesis of available evidence and indicate in which direction it is worthwhile to prompt further research. We performed a systematic literature review on the usability of mobile applications for people with visual impairments. A deep analysis following the Preferred Reporting Items for SLRs and Meta-Analyses (PRISMA) guidelines was performed to produce a set of relevant papers in the field. We first identified 932 papers published within the last six years. After screening the papers and employing a snowballing technique, we identified 60 studies that were then classified into seven themes: accessibility, daily activities, assistive devices, navigation, screen division layout, and audio guidance. The studies were then analyzed to answer the proposed research questions in order to illustrate the different trends, themes, and evaluation results of various mobile applications developed in the last six years. Using this overview as a foundation, future directions for research in the field of usability for the visually impaired (UVI) are highlighted.

37 **KEYWORDS:** Usability, accessibility, Systematic Literature Review (SLR)

Introduction

40   The era of mobile devices and applications has begun. With the widespread use of mobile
41 applications, designers and developers need to consider all types of users and develop
42 applications for their different needs. One notable group of users is people with visual
43 impairments. According to the World Health Organization, there are approximately 285 million
44 people with visual impairments worldwide (WHO, 2020). This is a huge number to keep in mind
45 while developing new mobile applications.

46   People with visual impairments have urged more attention from the tech community to
47 provide them with the assistive technologies they need (Khan & Khusro, 2021). Small tasks that
48 we do daily, such as picking out outfits or even moving from one room to another, could be
49 challenging for such individuals. Thus, leveraging technology to assist with such tasks can be life
50 changing. Besides, increasing the usability of applications and developing dedicated ones
51 tailored to their needs is essential. The usability of an application refers to its efficiency in terms
52 of the time and effort required to perform a task, its effectiveness in performing said tasks, and
53 its users' satisfaction (Ferreira, 2020). Researchers have been studying this field intensively and
54 proposing different solutions to improve the usability of applications for people with visual
55 impairments.

56   This paper provides a systematic literature review (SLR) on the usability of mobile
57 applications for people with visual impairments. The study aims to find discussions of usability
58 issues related to people with visual impairments in recent studies and how they were solved
59 using mobile applications. By reviewing published works from the last six years, this SLR aims
60 to update readers on the newest trends, limitations of current research, and future directions in
61 the research field of usability for the visually impaired (UVI).

62   This SLR can be of great benefit to researchers aiming to become involved in UVI
63 research and could provide the basis for new work to be developed, consequently improving the
64 quality of life for the visually impaired. This review differs from previous review studies (i.e.
65 Khan & Khusro, 2021) because we classified the studies into themes in order to better evaluate
66 and synthesize the studies and provide clear directions for future work. The following themes
67 were chosen based on the issues addressed in the reviewed papers: "Assistive Devices,"
68 "Navigation," "Accessibility," "Daily Activities," "Audio Guidance," and "Gestures." Figure 1
69 illustrates the percentage of papers classified in each theme.

70 *Figure 1: Percentages of classification themes*

71   The remainder of this paper is organized as follows: the next section specifies the
72 methodology, following this, the results section illustrates the results of the data collection, the
73 discussion section consists of the research questions with their answers and the limitations and

74 potential directions for future work, and the final section summarizes this paper's main findings
75 and contribution.

76

Survey Methodology

78 This systematic literature review used the Meta-Analyses (PRISMA, 2009) guidelines to
79 produce a set of relevant papers in the field. This SLR was undertaken to address the research
80 questions described below. A deep analysis was performed based on a group of studies; the most
81 relevant studies were documented, and the research questions were addressed.

82 **A. RESEARCH QUESTIONS**
83 The research questions addressed by this study are presented in Table 1 with descriptions and
84 the motivations behind them.

85 *Table 1: Research questions*

86 **B. SEARCH STRATEGY**

87 This review analysed and synthesised studies on usability for the visually impaired from a
88 user perspective following a systematic approach. As proposed by Tranfield et al. (Tanfield,
89 Denyer & Smart, 2003), the study followed a three-stage approach to ensure that the findings
90 were both reliable and valid. These stages were planning the review, conducting the review by
91 analysing papers, and reporting emerging themes and recommendations. These stages will be
92 discussed further in the following section.

93 1. **PLANNING STAGE**
94 The planning stage of this review included defining data sources and the search string
95 protocol as well as inclusion and exclusion criteria.

96 ➢ DATA SOURCES

97 We aimed to use two types of data sources: digital libraries and search engines. The search
98 process was manually conducted by searching through databases. The selected databases and
99 digital libraries are as follows:

100 • ACM Library
101 • IEEE Xplore
102 • ScienceDirect
103 • SpringerLink
104 • ISI Web of Knowledge
105 • Scopus.

106   The selected search engines were as follows:

107   • DBLP (Computer Science Bibliography Website)
108   • Google Scholar
109   • Microsoft Academic
110
111   ➢ SEARCH STRING

112   The above databases were initially searched using the following keyword protocol:
113   ("Usability" AND ("visual impaired" OR "visually impaired" OR "blind" OR "impairment")
114   AND "mobile"). However, in order to generate a more powerful search string, the Network
115   Analysis Interface for Literature Studies (NAILS) project was used. NAILS is an automated tool
116   for literature analysis. Its main function is to perform statistical and social network analysis
117   (SNA) on citation data (Knutas et al., 2015). In this study, it was used to check the most
118   important work in the relevant fields as shown in figure 2.
119   NAILS produced a report displaying the most important authors, publications, and keywords
120   and listed the references cited most often in the analysed papers (Knutas et al., 2015) . The new
121   search string was generated after using the NAILS project as follows: ("Usability" OR "usability
122   model" OR "usability dimension" OR "Usability evaluation model" OR "Usability evaluation
123   dimension") AND ("mobile" OR "Smartphone") AND ("Visually impaired" OR "Visual
124   impairment" OR "Blind" OR "Low vision" OR "Blindness").

125   *Figure 2: NAILS output sample*

126   ➢ INCLUSION AND EXCLUSION CRITERIA

127   To be included in this systematic review, each study had to meet the following screening
128 criteria:

- 129   The study must have been published between 2015 and 2020.
- 130   The study must be relevant to the main topic (Usability of Mobile Applications for
131   Visually Impaired Users).
- 132   The study must be a full-length paper.
- 133   The study must be written in English because any to consider any other languages,
134   the research team will need to use the keywords of this language in this topic and
135   deal with search engines using that language to extract all studies related to our
136   topic to form an SLR with a comprehensive view of the selected languages.
137   Therefore, the research team preferred to focus on studies in English to narrow the
138   scope of this SLR.

139   A research study was excluded if it did not meet one or more items of the criteria.

140 **2. CONDUCTING STAGE:**

141   The conducting stage of the review involved a systematic search based on relevant search
142 terms. This consisted of three substages: exporting citations, importing citations into Mendeley,
143 and importing citations into Rayyan.

144 ➢ EXPORTING CITATIONS

145   First, in exporting the citations and conducting the search through the mentioned
146 databases, a total of 932 studies were found. The numbers are illustrated in Figure 4 below. The
147 highest number of papers was found in Google Scholar, followed by Scopus, ISI Web of
148 Knowledge, ScienceDirect, IEEE Xplore, Microsoft Academic, and DBLP and ACM Library
149 with two studies each. Finally, SpringerLink did not have any studies that met the inclusion
150 criteria.

151 *Figure 3: Number of papers per database*

152   The chance of encountering duplicate studies was determined to be high. Therefore,
153 importing citations into Mendeley was necessary in order to eliminate the duplicates.

154 ➢ IMPORTING CITATIONS INTO MENDELEY

155   Mendeley is an open-source reference and citation manager. It can highlight paragraphs
156 and sentences, and it can also list automatic references on the end page. Introducing the use of
157 Mendeley is also expected to avoid duplicates in academic writing, especially for systematic
158 literature reviews (Basri & Patak, 2015). Hence, in the next step, the 932 studies were imported
159 into Mendeley, and each study's title and abstract were screened independently for eligibility. A
160 total of 187 duplicate studies were excluded. 745 total studies remained after the first elimination
161 process.

162 *Figure 4: Search stages*

163 ➤ IMPORTING CITATIONS INTO RAYYAN

164 Rayyan QCRI is a free web and mobile application that helps expedite the initial screening
165 of both abstracts and titles through a semi-automated process while incorporating a high level of
166 usability. Its main benefit is to speed up the most tedious part of the systematic literature review
167 process: selecting studies for inclusion in the review (Ouzzani et al., 2016). Therefore, for the
168 last step, another import was done using Rayyan to check for duplications a final time. Using
169 Rayyan, a total of 124 duplicate studies were found, resulting in a total of 621 studies. Using
170 Rayyan, a two-step filtration was conducted to guarantee that the papers have met the inclusion
171 criteria of this SLR. After filtering based on the abstracts, 564 papers did not meet the inclusion
172 criteria. At this stage, 57 studies remained. The second step of filtration eliminated 11 more
173 studies by reading the full papers; two studies were not written in the English language, and nine
174 were inaccessible.

175 ➤ SNOWBALLING

176 Snowballing is an emerging technique used to conduct systematic literature reviews that are
177 considered both efficient and reliable using simple procedures. The procedure for snowballing
178 consisted of three phases in each cycle. The first phase is refining the start set, the second phase
179 is backward snowballing, and the third is forward snowballing. The first step, forming the start
180 set, is basically identifying relevant papers that can have a high potential of satisfying the criteria
181 and research question. Backward snowballing was conducted using the reference list to identify
182 new papers to include. It shall start by going through the reference list and excluding papers that
183 do not fulfill the basic criteria; the rest that fulfil criteria shall be added to the SLR. Forward
184 snowballing refers to identifying new papers based on those papers that cited the paper being
185 examined (Juneja & Kaur, 2019). Hence, in order to be sure that we concluded all related studies
186 after we got the 46 papers, a snowballing step was essential. Forward and backward snowballing
187 were conducted. Each of the 46 studies was examined by checking their references to take a look
188 at any possible addition of sources and examining all papers that cited this study. The
189 snowballing activity added some 38 studies, but after full reading, it became 33 that matched the
190 inclusion criteria. A total of 79 studies were identified through this process.

191 ➤ QUALITY ASSESSMENT

192 A systematic literature review's quality is determined by the content of the papers included in the
193 review. As a result, it is important to evaluate the papers carefully (Zhou et al., 2015). Many
194 influential scales exist in the software engineering field for evaluating the validity of individual
195 primary studies and grading the overall intensity of the body of proof. Hence, we adapted the
196 comprehensive guidelines specified by Kitchenhand and Charters (Keele, 2007), and the quasi-
197 gold standard (QGS) (Keele, 2007) was used to establish the quest technique, where a robust
198 search strategy for enhancing the validity and reliability of a SLR's search process is devised
199 using the QGS. By applying this technique, our quality assessment questions were focused and
200 aligned with the research questions mentioned earlier.

201   In our last step, we had to verify the papers' eligibility; we conducted a quality check for
202 each of the 79 studies. For quality assessment, we considered whether the paper answered the
203 following questions:
204 QA1: Is the research aim clearly stated in the research?
205 QA2: Does the research contain a usability dimension or techniques for mobile applications for
206 people with visual impairments?
207 QA3: Is there an existing issue with mobile applications for people with visual impairments that
208 the author is trying to solve?
209 QA4: Is the research focused on mobile application solutions?
210 After discussing the quality assessment questions and attempting to find an answer in each paper,
211 we agreed to score each study per question. If the study answers a question, it will be given 2
212 points; if it only partially answers a question, it will be given 1 point; and if there is no answer
213 for a given question in the study, it will have 0 points.
214   The next step was to calculate the weight of each study. If the total weight was higher or
215 equal to four points, the paper was accepted in the SLR; if not, the paper was discarded since it
216 did not reach the desired quality level. Figure 5 below illustrates the quality assessment process.
217 After applying the quality assessment, 39 papers were rejected since they received less than four
218 points, which resulted in a final tally of 60 papers.

219 *Figure 5: Quality assessment process*

220   To summarize, this review was conducted according to the Preferred Reporting Items for
221 SLRs and Meta-Analyses (PRISMA) (Liberati et al., 2009). The PRISMA diagram shown in
222 Figure 6 illustrates all systematic literature processes used in this study.

223 *Figure 6: PRISMA flow diagram*

224 **3. ANALYSING STAGE:**
225   All researchers involved in this SLR collected the data. The papers were distributed equally
226 between them, and each researcher read each paper completely to determine its topic, extract the
227 paper's limitations and future work, write a quick summary about it, and record this information
228 in an Excel spreadsheet.
229

230 **RESULTS**

231   All researchers worked intensively on this systematic literature review. After completing the
232 previously mentioned steps, the papers were divided among all the researchers. Then, each
233 researcher read their assigned papers completely and then classified them into themes according
234 to the topic they covered. The researchers held several meetings to discuss and specify those
235 themes. The themes were identified by the researchers based on the issues addressed in the
236 reviewed papers. In the end, the researchers resulted in seven themes, as shown in Figure 7

237 below. The references selected for each theme can be found in the Appendix. Afterwards, each
238 researcher was assigned one theme to summarize its studies and report the results. In this
239 section, we review the results.

240 ***Figure 7: Results of the SLR***

241 **A. Accessibility**
242   Of a total of 60 studies, 10 focused on issues of accessibility. Accessibility is concerned with
243 whether all users are able to have equivalent user experiences, regardless of abilities. Six studies,
244 (Darvishy, Hutter & Frei, 2019), (Morris et al., 2016), (Qureshi & Wong, 2020), (Khan, Khusro
245 & Alam, 2018) , (Paiva et al., 2020), and (Pereda, Murillo & Paz, 2020), gave suggestions for
246 increasing accessibility, (Darvishy, Hutter & Frei, 2019), and (Morris et al., 2016), gave some
247 suggestions for making mobile map applications and Twitter accessible to visually impaired
248 users, and (Qureshi & Wong, 2020) and (Khan, Khusro & Alam, 2018) focused on user
249 interfaces and provided accessibility suggestions suitable for blind people. (Paiva et al., 2020)
250 and (Pereda, Murillo & Paz, 2020) proposed a set of heuristics to evaluate the accessibility of
251 mobile applications. Two studies, (Khowaja et al., 2019) and (Carvalho et al., 2018), focused on
252 evaluating usability and accessibility issues on some mobile applications, comparing them, and
253 identifying the number and types of problems that visually impaired users faced. (Aqle, Khowaja
254 & Al-Thani, 2020) proposed a new web search interface designed for visually impaired users.
255 One study, (McKay, 2017), focused on accessibility challenges by applying usability tests on a
256 hybrid mobile app with some visually impaired university students.
257

258 **B. Assistive Devices**
259   People with visual impairments have an essential need for assistive technology since they
260 face many challenges when performing activities in daily life. Out of the 60 studies reviewed, 13
261 were related to assistive technology. The studies (Smaradottir, Martinez & Håland, 2017),
262 (Skulimowski et al.,2019), (Barbosa, Hayes & Wang, 2016), (Rosner & Perlman, 2018), (Csapó
263 et al., 2015), (Khan & Khusro, 2020), (Sonth & Kallimani, 2017), (Kim et al., 2016), (Vashistha
264 et al., 2015), (Kameswaran et al., 2020), (Shirley et al., 2017), and (Rahman et al., 2017) were
265 related to screen readers (voiceovers). On the other hand, (Bharatia, Ambawane & Rane, 2019)
266 and (Lewis et al., 2016) were related to proposing an assistant device for the visually impaired.
267 Of the studies related to screening readers, (Sonth & Kallimani, 2017), (Vashistha et al., 2015),
268 (Khan & Khusro, 2020) and (Lewis et al.,2016) cited challenges faced by visually impaired
269 users. Barbosa, Hayes & Wang, 2016) , (Kim et al., 2016), and (Rahman et al., 2017) suggested
270 new applications, while (Smaradottir, Martinez & Håland, 2017), (Rosner & Perlman, 2018),
271 (Csapó et al., 2015), and (Shirley et al., 2017) evaluated current existing work. The studies
272 (Bharatia, Ambawane & Rane, 2019) and (Lewis et al., 2016) proposed using wearable devices
273 to improve the quality of life for people with visual impairments.
274

C. Daily Activities

In recent years, people with visual impairments have used mobile applications to increase their independence in their daily activities and learning, especially those based on the braille method. We divide the daily activity section into braille-based applications and applications designed to enhance the independence of the visually impaired. Four studies, (Nahar, Sulaiman, & Jaafar, 2020), (Nahar, Jaafar, & Sulaiman, 2019), (Araújo et al., 2016), and (Gokhale et al., 2017), implemented and evaluated the usability of mobile phone applications that use braille to help visually impaired people in their daily lives. Seven studies, (Vitiello et al., 2018), (Kunaratana-Angkul, Wu, & Shin-Renn, 2020), (Ghidini et al., 2016), (Madrigal-Cadavid et al., 2019), (Marques, Carriço & Guerreiro, 2015), (Oliveira et al., 2018), and (Rodrigues et al., 2015), focused on building applications that enhance the independence and autonomy of people with visual impairments in their daily life activities.

D. Screen Division Layout

People with visual impairments encounter various challenges in identifying and locating non-visual items on touch screen interfaces like phones and tablets. Incidents of accidentally touching a screen element and frequently following an incorrect pattern in attempting to access objects and screen artifacts hinder blind people from performing typical activities on smartphones (Khusro et al., 2019). In this review, 9 out of 60 studies discuss screen division layout: (Khusro et al., 2019), (Khan, & Khusro, 2019), (Grussenmeyer & Folmer, 2017), (Palani et al., 2018), and (Leporini & Palmucci, 2018) discuss touch screen (smartwatch tablets, mobile phones, and tablet) usability among people with visual impairments, while (Cho & Kim, 2017), (Alnfiai & Sampalli, 2016), (Niazi et al., 2016), and (Alnfiai & Sampalli, 2019) concern text entry methods that increase the usability of apps among visually impaired people. (Khusro et al., 2019) provides a novel contribution to the literature regarding considerations that can be used as guidelines for designing a user-friendly and semantically enriched user interface for blind people. An experiment in (Cho & Kim, 2017) was conducted comparing the two-button mobile interface usability with the one-finger method and voiceover. (Leporini & Palmucci, 2018) gathered information on the interaction challenges faced by visually impaired people when answering questions on a mobile touch-screen device, investigated possible solutions to overcome the accessibility and usability challenges.

E. Gestures

In total, 3 of 60 studies discuss gestures in usability. (Alnfiai & Sampalli, 2017) compared the performance of BrailleEnter, a gesture based input method to the Swift Braille keyboard, a method that requires finding the location of six buttons representing braille dot, while (Buzzi et al., 2017) and (Smaradottir, Martinez & Haland, 2017) provide an analysis of gesture performance on touch screens among visually impaired people.

314   **F. Audio Guidance**
315   People with visual impairment primarily depend on audio guidance forms in their daily lives;
316   accordingly, audio feedback helps guide them in their interaction with mobile applications.
317   Four studies discussed the use of audio guidance in different contexts: one in navigation (Gintner
318   et al., 2017), one in games (Araʹujo et al., 2017), one in reading (Sabab & Ashmafee, 2016), and
319   one in videos (Façanha et al., 2016).These studies were developed and evaluated based on
320   usability and accessibility of the audio guidance for people with visual impairments and aimed to
321   utilize mobile applications to increase the enjoyment and independence of such individuals.
322

323   **G. Navigation**
324   Navigation is a common issue that visually impaired people face. Indoor navigation is widely
325   discussed in the literature. (Nair et al., 2020), (Al-Khalifa & Al-Razgan, 2016), and (de Borba
326   Campos et al., 2015) discuss how we can develop indoor navigation applications for visually
327   impaired people. Outdoor navigation is also common in the literature, as seen in (Darvishy et al.,
328   2020), (Hossain, Qaiduzzaman & Rahman, 2020), (Long et al., 2016), (Prerana et al., 2019), and
329   (Bandukda et al., 2020). For example, in (Darvishy et al., 2020), Touch Explorer, an accessible
330   digital map application, was presented to alleviate many of the problems faced by people with
331   visual impairments while using highly visually oriented digital maps. Primarily, it focused on
332   using non-visual output modalities like voice output, everyday sound, and vibration feedback.
333   Issues with navigation applications were also presented in (Maly et al., 2015). (Kameswaran et
334   al., 2020) discussed commonly used technologies in navigation applications for blind people and
335   highlighted the importance of using complementary technologies to convey information through
336   different modalities to enhance the navigation experience. Interactive sonification of images for
337   navigation has also been shown in (Skulimowski et al., 2019).
338

339   # DISCUSSION
340   In this section, the research questions are addressed in detail to clearly achieve the research
341   objective. Also, a detailed overview of each theme will be mentioned below.
342

343   **Answers to the Research Questions**
344   This section will answer the research question proposed:
345

346   **RQ1: What existing UVI issues did authors try to solve with mobile devices?**
347   Mobile applications can help people with visual impairments in their daily activities, such as
348   navigation and writing. Additionally, mobile devices may be used for entertainment purposes.
349   However, people with visual impairments face various difficulties while performing text entry
350   operations, text selection, and text manipulation on mobile applications (Niazi et al., 2016).
351   Thus, the authors of the studies tried to increase touch screens' usability by producing prototypes
352   or simple systems and doing usability testing to understand the UX of people with visual
353   impairments.

RQ2: What is the role of mobile devices in solving those issues?

Mobile phones are widely used in modern society, especially among users with visual impairments; they are considered the most helpful tool for blind users to communicate with people worldwide (Smaradottir, Martinez & Håland, 2017). In addition, the technology of touch screen assistive technology enables speech interaction between blind people and mobile devices and permits the use of gestures to interact with a touch user interface. Assistive technology is vital in helping people living with disabilities perform actions or interact with systems (Niazi et al., 2016).

RQ3: What are the publication trends on the usability of mobile applications among the visually impaired?

As shown in Figure 8 below, research into mobile applications' usability for the visually impaired has increased in the last five years, with a slight dip in 2018. Looking at the most frequent themes, we find that "Assistive Devices" peaked in 2017, while "Navigation" and "Accessibility" increased significantly in 2020. On the other hand, we see that the prevalence of "Daily Activities" stayed stable throughout the research years. The term "Audio Guidance" appeared in 2016 and 2017 and has not appeared in the last three years. "Gestures" also appeared only in 2017. "Screen Layout Division" was present in the literature in the last five years and increased in 2019 but did not appear in 2020.

Figure 8: Publication trends over time

RQ4: What are the current research limitations and future research directions regarding usability among the visually impaired?

We divide the answer to this question into two sections: first, we will discuss limitations; then, we will discuss future work for each proposed theme.

A. Limitations

Studies on the usability of mobile applications for visually impaired users in the literature have various limitations, and most of them were common among the studies. These limitations were divided into two groups. The first group concerns proposed applications; for example, (Rahman et al., 2017), (Oliveira et al., 2018), and (Madrigal-Cadavid et al., 2019) faced issues regarding camera applications in mobile devices due to the considerable effort needed for its usage and being heavily dependent on the availability of the internet. The other group of studies, (Rodrigues et al., 2015), (Leporini & Palmucci, 2018), (Alnfiai & Sampalli, 2016), and (Araújo et al., 2017), have shown limitations in visually impaired users' inability to comprehend a graphical user interface. (Alnfiai & Sampalli, 2017) and (Alnfiai & Sampalli, 2019) evaluated new braille input methods and found that the traditional braille keyboard, where knowing the exact position of letters QWERTY is required, is limited in terms of usability compared to the new input methods. Most studies faced difficulties regarding the sample size and the fact that many of the participants were not actually blind or visually impaired but only blindfolded. This

392 likely led to less accurate results, as blind or visually impaired people can provide more useful
393 feedback as they experience different issues on a daily basis and are more ideal for this type of
394 study. So, the need for a good sample of participants who actually have this disability is clear to
395 allow for better evaluation results and more feedback and recommendations for future research.
396 **B. Future Work**
397   A commonly discussed future work in the chosen literature is to increase the sample sizes of
398 people with visual impairment and focus on various ages and geographical areas to generalize
399 the studies. Table 2 summarizes suggestions for future work according to each theme. Those
400 future directions could inspire new research in the field.

401 *Table 2: Theme-based future work*

402 **RQ5: What is the focus of research on usability for visually impaired people, and what are**
403 **the research outcomes in the studies reviewed?**
404   There are a total of 60 outcomes in this research. Of these, 40 involve suggestions to improve
405 usability of mobile applications; four of them address problems that are faced by visually
406 impaired people that reduce usability. Additionally, 16 of the outcomes are assessments of the
407 usability of the prototype or model. Two of the results are recommendations to improve
408 usability. Finally, the last two outcomes are hardware solutions that may help the visually
409 impaired perform their daily activities. Figure 9 illustrates these numbers.

410 *Figure 9: Outcomes of studies*

411 **Overview of the reviewed studies**
412   In the following subsections, we summarize all the selected studies based on the classified
413 theme: accessibility, assistive devices, daily activities, screen division layout, gestures, audio
414 guidance, and navigation. The essence of the studies will be determined, and their significance in
415 the field will be explored.
416

417 **A. Accessibility**
418   For designers dealing with mobile applications, it is critical to determine and fix accessibility
419 issues in the application before it is delivered to the users (Khowaja et al., 2019). Accessibility
420 refers to giving the users the same user experience regardless of ability. In (Khowaja et al., 2019)
421 and (Carvalho et al., 2018), the researchers focused on comparing the levels of accessibility and
422 usability in different applications. They had a group of visually impaired users and a group of
423 sighted users test out the applications to compare the number and type of problems they faced
424 and determine which applications contained the most violations. Because people with visual
425 impairments cannot be ignored in the development of mobile applications, many researchers
426 have sought solutions for guaranteeing accessibility. For example, in (Qureshi & Wong, 2020),
427 the study contributed to producing a new, effective design for mobile applications based on the
428 suggestions of people with visual impairments and with the help of two expert mobile
429 application developers. In (Khan, Khusro & Alam, 2018), an adaptive user interface model for

430 visually impaired people was proposed and evaluated in an empirical study with 63 visually
431 impaired people. In (Aqle, Khowaja & Al-Thani,2020), the researchers proposed a new web
432 search interface for users with visual impairments that is based on discovering concepts through
433 formal concept analysis (FCA). Users interact with the interface to collect concepts, which are
434 then used as keywords to narrow the search results and target the web pages containing the
435 desired information with minimal effort and time. The usability of the proposed search interface
436 (InteractSE) was evaluated by experts in the field of HCI and accessibility, with a set of
437 heuristics by Nielsen and a set of WCAG 2.0 guidelines.
438   In (Darvishy, Hutter & Frei, 2019), the researchers proposed a solution for making mobile
439 map applications accessible for people with blindness or visual impairment. They suggested
440 replacing forests in the map with green color and birds' sound, replacing water with blue color
441 and water sounds, replacing streets with grey color and vibration, and replacing buildings with
442 yellow color and pronouncing the name of the building. The prototype showed that it was
443 possible to explore a simple map through vibrations, sounds, and speech.
444   In (Morris et al., 2016), the researchers utilized a multi-faceted technique to investigate how
445 and why visually impaired individuals use Twitter and the difficulties they face in doing so. They
446 noted that Twitter had become more image-heavy over time and that picture-based tweets are
447 largely inaccessible to people with visual impairments. The researchers then made several
448 suggestions for how Twitter could be amended to continue to be usable for people with visual
449 impairments.
450   The researchers in (Paiva et al., 2020) focused on how to evaluate proposed methods for
451 ensuring the accessibility and usability of mobile applications. Their checklist, Acc-
452 MobileCheck, contains 47 items that correspond to issues related to comprehension (C),
453 operation (O), perception (P), and adaptation (A) in mobile interface interaction. To validate
454 Acc-MobileCheck, it was reviewed by five experts and three developers and determined to be
455 effective. In (Pereda, Murillo & Paz, 2020), the authors also suggest a set of heuristics to
456 evaluate the accessibility of mobile e-commerce applications for visually impaired people.
457 Finally, (McKay, 2017) conducted an accessibility test for hybrid mobile apps and found that
458 students with blindness faced many barriers to access based on how they used hybrid mobile
459 applications. While hybrid apps can allow for increased time for marketing, this comes at the
460 cost of app accessibility for people with disabilities.
461

462 **B. Assistive Devices**
463   A significant number of people with visual impairments use state-of-the-art software to
464 perform tasks in their daily lives. These technologies are made up of electronic devices equipped
465 with sensors and processors that can make intelligent decisions.
466   One of the most important and challenging tasks in developing such technologies is to create
467 a user interface that is appropriate for the sensorimotor capabilities of users with blindness
468 (Csapó et al., 2015). Several new hardware tools have proposed to improve the quality of life for
469 people with visual impairments. Three tools were presented in this SLR: a smart stick that can

470   notify the user of any obstacle, helping them to perform tasks easily and efficiently (Bharatia,
471   Ambawane & Rane, 2019), and an eye that can allow users to detect colors (medical evaluation
472   is still required) (Lewis et al.,2016).

473   The purpose of the study in (Shirley et al., 2017) was to understand how people with
474   blindness use smartphone applications as assistive technology and how they perceive them in
475   terms of accessibility and usability. An online survey with 259 participants was conducted, and
476   most of the participants rated the applications as useful and accessible and were satisfied with
477   them.

478   The researchers in (Rahman et al., 2017) designed and implemented EmoAssist, which is a
479   smartphone application that assists with natural dyadic conversations and aims to promote user
480   satisfaction by providing options for accessing non-verbal communication that predicts
481   behavioural expressions and contains interactive dimensions to provide valid feedback. The
482   usability of this application was evaluated in a study with ten people with blindness where
483   several tools were applied in the application. The study participants found that the usability of
484   EmoAssist was good, and it was an effective assistive solution.

485

486   **C. Daily Activities**

487   This theme contains two main categories: braille-based application studies and applications
488   to enhance the independence of VIU. Both are summarized below.

489   1- Braille-based applications

490   Braille is still the most popular method for assisting people with visual impairments in
491   reading and studying, and most educational mobile phone applications are limited to sighted
492   people. Recently, however, some researchers have developed assistive education applications for
493   students with visual impairments, especially those in developing countries. For example, in
494   India, the number of children with visual impairments is around 15 million, and only 5% receive
495   an education (Gokhale et al., 2017). Three of the braille studies focused on education: (Nahar,
496   Sulaiman, & Jaafar, 2020), (Nahar, Jaafar, & Sulaiman, 2019), and (Araújo et al., 2016). These
497   studies all used smartphone touchscreens and action gestures to gain input from the student, and
498   then output was provided in the form of audio feedback. In (Nahar, Sulaiman, & Jaafar, 2020),
499   vibrational feedback was added to guide the users. The participants in (Nahar, Sulaiman, &
500   Jaafar, 2020), (Nahar, Jaafar, & Sulaiman, 2019), and (Araújo et al., 2016) included students
501   with blindness of visual impairment and their teachers. The authors in (Nahar, Sulaiman, &
502   Jaafar, 2020) and (Nahar, Jaafar, & Sulaiman, 2019) evaluated the usability of their applications
503   following the same criteria (efficiency, learnability, memorability, errors, and satisfaction). The
504   results showed that in (Nahar, Sulaiman, & Jaafar, 2020), (Nahar, Jaafar, & Sulaiman, 2019), and
505   (Araújo et al., 2016), the applications met the required usability criteria. The authors in (Gokhale
506   et al., 2017) presented a braille-based solution to help people with visual impairments call and
507   save contacts. A braille keypad on the smartphone touchscreen was used to gain input from the
508   user, which was then converted into haptic and auditory feedback to let the user know what
509   action was taken. The usability of this application was considered before it was designed. The

510 participants' responses were positive because this kind of user-centric design simplifies
511 navigation and learning processes.

512 2- Applications to Enhance the Independence of People with Visual Impairments

513   The authors in the studies explored in this section focused on building applications that
514 enhance independence and autonomy in daily life activities for users with visual impairments.

515   In (Vitiello et al., 2018), the authors presented their mobile application, an assistive solution
516 for visually impaired users called "Crania", which uses machine learning techniques to help
517 users with visual impairments get dressed by recognizing the colour and texture of their clothing
518 and suggesting suitable combinations. The system provides feedback through voice synthesis.
519 The participants in the study were adults and elderly people, some of whom were completely
520 blind and the rest of whom had partial sight. After testing for usability, all the participants with
521 blindness agreed that using the application was better than their original method, and half of the
522 participants with partial sight said the same thing. At the end of the study, the application was
523 determined to be accessible and easy to use.

524   In (Kunaratana-Angkul, Wu, & Shin-Renn, 2020), an application which allows elderly
525 people to measure low vision status at home through their smartphones instead of visiting
526 hospitals was tested, and most of the participants considered it to be untrustworthy because the
527 medical information was insufficient. Even when participants were able to learn how to use the
528 application, most of them were still confused while using it and needed further instruction.

529   In (Ghidini et al., 2016), the authors studied the habits of people with visual impairments
530 when using their smartphones in order to develop an electronic calendar with different
531 interaction formats, such as voice commands, touch, and vibration interaction. The authors
532 presented the lessons learned and categorized them based on usability heuristics such as
533 feedback, design, user freedom and control, and recognition instead of remembering.

534   In (Madrigal-Cadavid et al., 2019), the authors developed a drug information application for
535 people with visual impairments to help them access the labels of medications. The application
536 was developed based on a user-centered design process. By conducting a usability test, the
537 authors recognized some usability issues for people with visual impairments, such as difficulty in
538 locating the bar code. Given this, a new version will include a search function that is based on
539 pictures. The application is searched by capturing the bar code or text or giving voice commands
540 that allow the user to access medication information. The participants were people with visual
541 impairments, and most of them required assistance using medications before using the
542 application. This application will enhance independence for people with visual impairments in
543 terms of using medications.

544   In (Marques, Carriço & Guerreiro, 2015), an authentication method is proposed for users
545 with visual impairments that allows them to protect their passwords. It is not secure when blind
546 or visually impaired users spell out their passwords or enter the numbers in front of others, and
547 the proposed solution allows the users to enter their password with one hand by tapping the
548 screen. The blind participants in this study demonstrated that this authentication method is usable
549 and supports their security needs.

550   In (Oliveira et al., 2018), the author noted that people with visual impairments face
551   challenges in reading, thus he proposed an application called LeR´otulos. This application was
552   developed and evaluated for the Android operating system and recognizes text from photos taken
553   by the mobile camera and converts them into an audio description. The prototype was designed
554   to follow the guidelines and recommendations of usability and accessibility. The requirements of
555   the application are defined based on the following usability goals: the steps are easy for the user
556   to remember; the application is efficient, safe, useful, and accessible; and user satisfaction is
557   achieved.
558   Interacting with talkback audio devices is still difficult for people with blindness, and it is
559   unclear how much benefit they provide to people with visual impairments in their daily
560   activities. The author in (Rodrigues et al., 2015) investigates the smartphone adoption process of
561   blind users by conducting experiments, observations, and weekly interviews. An eight-week
562   study was conducted with five visually impaired participants using Samsung and an enabled
563   talkback 2 screen reader. Focusing on understanding the experiences of people with visual
564   impairments when using touchscreen smartphones revealed accessibility and usability issues.
565   The results showed that the participants have difficulties using smartphones because they fear
566   that they cannot use them properly, and that impacts their ability to communicate with family.
567   However, they appreciate the benefits of using smartphones in their daily activities, and they
568   have the ability to use them.
569

570 **D. Screen Division Layout**
571   People with visual impairments encounter various challenges identifying and locating non-
572   visual items on touch screen interfaces, such as phones and tablets. Various specifications for
573   developing a user interface for people with visual impairments must be met, such as having
574   touch screen division to enable people with blindness to easily and comfortably locate objects
575   and items that are non-visual on the screen (Khusro et al., 2019). Article (Khusro et al., 2019)
576   highlighted the importance of aspects of the usability analysis, such as screen partitioning, to
577   meet specific usability requirements, including orientation, consistency, operation, time
578   consumption, and navigation complexity when users want to locate objects on their touchscreen.
579   The authors of (Khan, & Khusro, 2019) describe the improvements that people with blindness
580   have experienced in using the smartphone while performing their daily tasks. This information
581   was determined through an empirical study with 41 people with blindness who explained their
582   user and interaction experiences operating a smartphone.
583   The authors in (Palani et al., 2018) provide design guidelines governing the accurate display
584   of haptically perceived graphical materials. Determining the usability parameters and the various
585   cognitive abilities required for optimum and accurate use of device interfaces is crucial. Also the
586   authors of (Grussenmeyer & Folmer, 2017) highlight the importance of usability and
587   accessibility of smartphones and touch screens for people with visual impairments. The primary
588   focus in (Leporini & Palmucci, 2018) is on interactive tasks used to finish exercises and to
589   answer questionnaires or quizzes. These tools are used for evaluation tests or in games. When

590   using gestures and screen readers to interact on a mobile device, difficulties may arise (Leporini
591   & Palmucci, 2018), The study has various objectives, including gathering information on the
592   difficulties encountered by people with blindness during interactions with mobile touch screen
593   devices to answer questions and investigating practicable solutions to solve the detected
594   accessibility and usability issues. A mobile app with an educational game was used to apply the
595   proposed approach. Moreover, in (Alnfiai & Sampalli, 2016) and (Niazi et al., 2016), an analysis
596   of the single-tap braille keyboard created to help people with no or low vision while using touch
597   screen smartphones was conducted. The technology used in (Alnfiai & Sampalli, 2016) was the
598   talkback service, which provides the user with verbal feedback from the application, allowing
599   users with blindness to key in characters according to braille patterns. To evaluate single tap
600   braille, it was compared to the commonly used QWERTY keyboard. In (Niazi et al., 2016), it
601   was found that participants adapted quickly to single-tap Braille and were able to type on the
602   touch screen within 15 to 20 minutes of being introduced to this system. The main advantage of
603   single tap braille is that it allows users with blindness to enter letters based on braille coding,
604   which they are already familiar with. The average error rate is lower using single-tap Braille than
605   it is on the QWERTY keyboard. The authors of (Niazi et al., 2016) found that minimal typing
606   errors were made using the proposed keypad, which made it an easier option for people with
607   blindness (Niazi et al., 2016). In (Cho & Kim, 2017), the authors describe new text entry
608   methods for the braille system including a left touch and a double touch scheme that form a two-
609   button interface for braille input so that people with visual impairments are able to type textual
610   characters without having to move their fingers to locate the target buttons.

611

E. Gestures

613   One of the main problems affecting the visually impaired is limited mobility for some
614   gestures. We need to know what gestures are usable by people with visual impairments.
615   Moreover, the technology of assistive touchscreen-enabled speech interaction between blind
616   people and mobile devices permits the use of gestures to interact with a touch user interface.
617   Assistive technology is vital in helping people living with disabilities to perform actions or
618   interact with systems. (Smaradottir, Martinez & Haland, 2017) analyses a voiceover screen
619   reader used in Apple Inc.'s products. An assessment of this assistive technology was conducted
620   with six visually impaired test participants. The main objectives were to pinpoint the difficulties
621   related to the performance of gestures applicable in screen interactions and to analyze the
622   system's response to the gestures. In this study, a user evaluation was completed in three phases.
623   The first phase entailed training users regarding different hand gestures, the second phase was
624   carried out in a usability laboratory where participants were familiarized with technological
625   devices, and the third phase required participants to solve different tasks. In (Knutas et al., 2015),
626   the vital feature of the system is that it enables the user to interactively select a 3D scene region
627   for sonification by merely touching the phone screen. It uses three different modes to increase
628   usability. (Alnfiai & Sampalli, 2017) explained a study done to compare the use of two data
629   input methods to evaluate their efficiency with completely blind participants who had prior

630 knowledge of braille. The comparison was made between the braille enter input method that uses
631 gestures and the swift braille keyboard, which necessitates finding six buttons representing
632 braille dots. Blind people typically prefer rounded shapes to angular ones when performing
633 complex gestures, as they experience difficulties performing straight gestures with right angles.
634 Participants highlighted that they experienced difficulties particularly with gestures that have
635 steep or right angles. In (Buzzi et al., 2017), 36 visually impaired participants were selected and
636 split into two groups of low-vision and blind people. They examined their touch-based gesture
637 preferences in terms of the number of strokes, multitouch, and shape angles. For this reason, a
638 wireless system was created to record sample gestures from various participants simultaneously
639 while monitoring the capture process.
640

641 **F. Audio Guidance**
642   People with visual impairment typically cannot travel without guidance due to the inaccuracy
643 of current navigation systems in describing roads and especially sidewalks. Thus, the author of
644 (Gintner et al., 2017) aims to design a system to guide people with visual impairments based on
645 geographical features and addresses them through a user interface that converts text to audio
646 using a built-in voiceover engine (Apple iOS). The system was evaluated positively in terms of
647 accessibility and usability as tested in a qualitative study involving six participants with visual
648 impairment.
649   Based on challenges faced by visually impaired game developers, (Araújo et al., 2017)
650 provides guidance for developers to provide accessibility in digital games by using audio
651 guidance for players with visual impairments. The interactions of the player can be conveyed
652 through audio and other basic mobile device components with criteria focused on the game level
653 and speed adjustments, high contrast interfaces, accessible menus, and friendly design. Without
654 braille, people with visual impairments cannot read, but braille is expensive and takes effort, and
655 so it is important to propose technology to facilitate reading for them. In (Sabab & Ashmafee,
656 2016), the author proposed developing a mobile application called "Blind Reader" that reads an
657 audio document and allows the user to interact with the application to gain knowledge. This
658 application was evaluated with 11 participants, and the participants were satisfied with the
659 application. Videos are an important form of digital media, and unfortunately people with visual
660 impairment cannot access these videos. Therefore, (Façanha et al., 2016) aims to discover sound
661 synthesis techniques to maximize and accelerate the production of audio descriptions with low-
662 cost phonetic description tools. This tool has been evaluated based on usability with eight people
663 and resulted in a high acceptance rate among users.
664

665 **G. Navigation**
666 1- Indoor Navigation
667   Visually impaired people face critical problems when navigating from one place to another.
668 Whether indoors or outdoors, they tend to stay in one place to avoid the risk of injury or seek the
669 help of a sighted person before moving (Al-Khalifa & Al-Razgan, 2016). Thus, aid in navigation

670   is essential for those individuals. In (Nair et al., 2020), Nair developed an application called
671   ASSIST, which leverages 19 Bluetooth low energy (BLE) beacons and augmented reality (AR)
672   to help visually impaired people move around cluttered indoor places (e.g., subways) and
673   provide the needed safe guidance, just like having a sighted person lead the way. In the subway
674   example, the beacons will be distributed across the halls of the subway and the application will
675   detect them. Sensors and cameras attached to the individual will detect their exact location and
676   send the data to the application. The application will then give a sequence of audio feedback
677   explaining how to move around the place to reach a specific point (e.g., "in 50 feet turn right",
678   "now turn left", "you will reach the destination in 20 steps"). The application also has an
679   interface for sighted and low-vision users that shows the next steps and instructions. A usability
680   study was conducted to test different aspects of the proposed solution. The majority of the
681   participants agreed that they could easily reach a specified location using the application without
682   the help of a sighted person. A survey conducted to give suggestions from the participants for
683   future improvements showed that most participants wanted to attach their phones to their bodies
684   and for the application to consider the different walking speeds of users. They were happy with
685   the audio and vibration feedback that was given before each step or turn they had to take.
686   In (Al-Khalifa & Al-Razgan, 2016), the main purpose of the study was to provide an Arabic-
687   language application for guidance inside buildings using Google Glass and an associated mobile
688   application. First, the building plan must be set by a sighted person who configures the different
689   locations needed. Ebsar will ask the map builder to mark each interesting location with a QR
690   code and generate a room number, and the required steps and turns are tracked using the mobile
691   device's built-in compass and accelerometer features. All of these are recorded in the application
692   for the use of a visually impaired individual, and at the end, a full map is generated for the
693   building. After setting the building map, a user can navigate inside the building with the help of
694   Ebsar, paired with Google Glass, for input and output purposes. The efficiency, effectiveness,
695   and levels of user satisfaction with this solution were evaluated. The results showed that the
696   errors made were few, indicating that Ebsar is highly effective. The time consumed in
697   performing tasks ranged from medium to low depending on the task; this can be improved later.
698   Interviews with participants indicated the application's ease of use. (de Borba Campos et al.,
699   2015) shows an application simulating a museum map for people with visual impairments. It
700   discusses whether mental maps and interactive games can be used by people with visual
701   impairments to recognize the space around them. After multiple usability evaluation sessions, the
702   mobile application showed high efficiency among participants in understanding the museum's
703   map without repeating the visitation. The authors make a few suggestions based on feedback
704   from the participants regarding enhancing usability, including using audio cues, adding
705   contextual help to realise the activities carried around in a space, and focusing on audio feedback
706   instead of graphics.
707   2-   Outdoor Navigation
708   Outdoor navigation is also commonly discussed in the literature. In (Darvishy et al., 2020),
709   Touch Explorer was presented to alleviate many of the problems faced by visually impaired

710   people in navigation by developing a non-visual mobile digital map. The application relies on
711   three major methods of communication with the user: voice output, vibration feedback, and
712   everyday sounds. The prototype was developed using simple abstract visuals and mostly relies
713   on voice for explanation of the content. Usability tests show the great impact the prototype had
714   on the understanding of the elements of the map. Few suggestions were given by the participants
715   to increase usability, including GPS localization to locate the user on the map, a scale element
716   for measuring the distance between two map elements, and an address search function.
717   In (Hossain, Qaiduzzaman & Rahman, 2020), a navigation application called Sightless Helper
718   was developed to provide a safe navigation method for people with visual impairments. It relies
719   on footstep counting and GPS location to provide the needed guidance. It can also ensure safe
720   navigation by detect objects and unsafe areas and can detect unusual shaking of the user and alert
721   an emergency contact about the problem. The user interaction categories are voice recognition,
722   touchpad, buttons, and shaking sensors. After multiple evaluations, the application was found to
723   be useful in different scenarios and was considered usable by people with visual impairments.
724   The authors in (Long et al., 2016) propose an application that uses both updates from users and
725   information about the real world to help visually impaired people navigate outdoor settings.
726   After interviews with participants, some design goals were set, including the ability to tag an
727   obstacle on the map, check the weather, and provide an emergency service. The application was
728   evaluated and was found to be of great benefit; users made few errors and found it easy to use. In
729   (Prerana et al., 2019), a mobile application called STAVI was presented to help visually impaired
730   people navigate from a source to a destination safely and avoid issues of re-routing. The
731   application depends on voice commands and voice output. The application also has additional
732   features, such as calling, messages, and emergency help. The authors in (Bandukda et al., 2020)
733   helped people with visual impairments explore parks and natural spaces using a framework
734   called PLACES. Different interviews and surveys were conducted to identify the issues visually
735   impaired people face when they want to do any leisure activity. These were considered in the
736   development of the framework, and some design directions were presented, such as the use of
737   audio to share an experience.
738   3- General Issues
739   The authors in (Maly et al., 2015) discuss implementing an evaluation model to assess the
740   usability of a navigation application and to understand the issues of communication with mobile
741   applications that people with visual impairments face. The evaluation tool was designed using a
742   client–server architecture and was applied to test the usability of an existing navigation
743   application. The tool was successful in capturing many issues related to navigation and user
744   behavior, especially the issue of different timing between the actual voice instruction and the
745   position of the user. The authors in (Kameswaran et al., 2020) conducted a study to find out
746   which navigation technologies blind people can use and to understand the complementarity
747   between navigation technologies and their impact on navigation for visually impaired users. The
748   results of the study show that visually impaired people use both assistive technologies and those
749   designed for non-visually impaired users. Improving voice agents in navigation applications was

750 discussed as a design implication for the visually impaired. In (Skulimowski et al.,2019), the
751 authors show how interactive sonification can be used in simple travel aids for the blind. It uses
752 depth images and a histogram called U-depth, which is simple auditory representations for blind
753 users. The vital feature of this system is that it enables the user to interactively select a 3D scene
754 region for sonification by touching the phone screen. This sonic representation of 3D scenes
755 allows users to identify the environment's general appearance and determine objects' distance.
756 The prototype structure was tested by three blind individuals who successfully performed the
757 indoor task. Among the test scenes used included walking along an empty corridor, walking
758 along a corridor with obstacles, and locating an opening between obstacles. However, the results
759 showed that it took a long time for the testers to locate narrow spaces between obstacles.

760 **RQ6: What evaluation methods were used in the studies on usability for visually impaired**
761 **people that were reviewed?**

762   The most prevalent methods to evaluate the usability of applications were surveys and
763 interviews. These were used to determine the usability of the proposed solutions and obtain
764 feedback and suggestions regarding additional features needed to enhance the usability from the
765 participants' points of view. Focus groups were also used extensively in the literature. Many of
766 the participants selected were blindfolded and were not actually blind or visually impaired.
767 Moreover, the samples selected for the evaluation methods mentioned above considered the age
768 factor depending on the study's needs.
769

Limitation and future work

771   The limitations of this paper are mainly related to the methodology followed. Focusing on just
772 eight online databases and restricting the search with the previously specified keywords and
773 string may have limited the number of search results. Additionally, a large number of papers
774 were excluded because they were written in other languages. Access limitations were also faced
775 due to some libraries asking for fees to access the papers. Therefore, for future works, a study to
776 expand on the SLR results and reveal the current usability models of mobile applications for the
777 visually impaired to verify the SLR results is needed so that this work contributes positively to
778 assessing difficulties and expanding the field of usability of mobile applications for users with
779 visual impairments.
780

Conclusions

782   In recent years, the number of applications focused on people with visual impairments has
783 grown, which has led to positive enhancements in those people's lives, especially if they do not
784 have people around to assist them. In this paper, the research papers focusing on Usability for
785 Visually Impaired Users were analyzed and classified into seven themes: accessibility, daily

786 activities, assistive devices, gestures, navigation, screen division layout, and audio guidance. We
787 found that various research studies focus on accessibility of mobile applications to ensure that
788 the same user experience is available to all users, regardless of their abilities. We found many
789 studies that focus on how the design of the applications can assist in performing daily life
790 activities like braille-based application studies and applications to enhance the independence of
791 VI users. We also found papers that discuss the role of assistive devices like screen readers and
792 wearable devices in solving challenges faced by VI users and thus improving their quality of life.
793 We also found that some research papers discuss limited mobility of some gestures for VI users
794 and investigated ways in which we can know what gestures are usable by people with visual
795 impairments. We found many research papers that focus on improving navigation for VI users by
796 incorporating different output modalities like sound and vibration. We also found various studies
797 focusing on screen division layout. By dividing the screen and focusing on visual impairment-
798 related issues while developing user interfaces, visually impaired users can easily locate the
799 objects and items on the screens. Finally, we found papers that focus on audio guidance to
800 improve usability. The proposed applications use voice-over and speech interactions to guide
801 visually impaired users in performing different activities through their mobiles. Most of the
802 researchers focused on usability in different applications and evaluated the usability issues of
803 these applications with visually impaired participants. Some of the studies included sighted
804 participants to compare the number and type of problems they faced. The usability evaluation
805 was generally based on the following criteria: accessibility, efficiency, learnability,
806 memorability, errors, safety, and satisfaction. Many of the studied applications show a good
807 indication of these applications' usability and follow the participants' comments to ensure
808 additional enhancements in usability. This paper aims to provide an overview of the
809 developments on usability of mobile applications for people with visual impairments and use this
810 overview to highlight potential future directions.
811

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1114 **Appendix**

1115 References selected for each theme
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Research questions

Table 1: Research questions

Research Question	Description and Motivation
RQ1: What existing UVI issues did authors try to solve with mobile devices?	The issues and proposed solutions will be of great significance for researchers as well as developers, providing a deeper understanding of whether a specific problem was addressed in the literature and what the proposed solutions were.
RQ2: What is the role of mobile devices in solving those issues?	Being able to identify the role of mobile devices in assisting visually impaired people in their daily lives will help improve their usability and provide a basis for future applications to be developed to improve quality of life for the visually impaired.
RQ3: What are the publication trends on the usability of mobile applications among the visually impaired?	After answering this question, it will become easier to classify the current existing work and the available application themes for the visually impaired.
RQ4: What are the current research limitations and future research directions regarding usability among the visually impaired?	This will help guide future research and open doors for new development.
RQ5: What is the focus of research on usability for visually impaired people, and what are the research outcomes in the studies reviewed?	Answering this question, will enable us to address the current focus of studies and the available ways to collect data.
RQ6: What evaluation methods were used in the studies on usability for visually impaired people that were reviewed?	This evaluation will help future researchers choose the most suitable methods according to the nature of their studies.

Theme-based future work

1   *Table 2: Theme-based future work*

Theme	Suggestions for Future Work	Sources
Accessibility	In terms of accessibility, in the future, there is potential in investigating concepts of how information will be introduced in a mobile application to increase accessibility VI users. In addition, future work directions include extending frameworks for visually complex or navigationally dense applications. Furthermore, emotion-based UI design may also be investigated to improve accessibility. Moreover, the optimization of GUI layouts and elements could be considered with a particular focus on gesture control systems and eye-tracking systems.	(Darvishy, Hutter & Frei, 2019), (Khan, Khusro & Alam, 2018), (Paiva et al., 2020), (Khowaja et al., 2019), and (Carvalho et al., 2018)
Assistive Devices	In terms of assistive devices for people with visual impairments, there is potential for future direction in research into multimodal non-visual interaction (e.g., sonification methods). Also, since there is very little available literature about how to go about prototype development and evaluation activities for assistive devices for users with no or little sight, it is important to investigate this to further develop the field.	(Skulimowski et al.,2019), (Bharatia, Ambawane & Rane, 2019), (Csapó et al., 2015), and (Rahman et al., 2017)
Daily Activities	There is a need to evaluate the usability and accessibility of applications that aim to assist visually impaired users and improve restrictions in daily activities.	(Madrigal-Cadavid et al., 2019) , (Oliveira et al., 2018), and (Rodrigues et al., 2015)
Screen Division Layout	In terms of screen division layout, it is important to continuously seek to improve interfaces and provide feedback to make them more focused, more cohesive, and simpler to handle. A complete set of robust design guidelines ought to be created to provide a wide variety of non-visual applications with increased haptic access on a touchscreen device.	(Khusro et al., 2019), (Alnfiai & Sampalli, 2019) , (Palani et al., 2018), and (Khan, & Khusro, 2019)
Gestures	Gesture based interaction ought to be further investigated as it has the potential to greatly improve the way VI users communicate with mobile devices. Performance of gestures with various sizes of touch screens ought to be compared, as the size might have a significant effect on what is considered a usable gesture.	(Alnfiai & Sampalli, 2017) and (Buzzi et al., 2017)
Navigation	Literature suggests that future work in the area of	

	navigation should focus on eliminating busy graphical interfaces and relying on sounds. Studying more methods and integrating machine learning algorithms and hardware devices to provide accurate results regarding the identification of surrounding objects, and continuous updates for any upcoming obstacles, is also discussed in the literature as an important direction for future work.	(Darvishy et al., 2020), (Hossain, Qaiduzzaman & Rahman, 2020), (Hossain, Qaiduzzaman & Rahman, 2020), and (Bandukda et al., 2020)
Audio Guidance	In terms of audio guidance, there is potential for future directions in expanding algorithms to provide audio guidance to assist in more situations. Authors also emphasise developing versions of the applications in more languages.	(Gintner et al., 2017), (Sabab & Ashmafee, 2016) and (Façanha et al., 2016)

Appendix 1

1   **Appendix**

2   References selected for each theme

No.	Name of the study	Category
1.	Making mobile map applications accessible for visually impaired people	Accessibility
2.	With most of it being pictures now, I rarely use it' Understanding Twitter's Evolving Accessibility to Blind Users.	Accessibility
3.	Usability of user-centric mobile application design from visually impaired people's perspective.	Accessibility
4.	Blindsense: An accessibility-inclusive universal user interface for blind people.	Accessibility
5.	Acc-MobileCheck: a Checklist for Usability and Accessibility Evaluation of Mobile Applications.	Accessibility
6.	Visually Impaired Accessibility Heuristics Proposal for e-Commerce Mobile Applications.	Accessibility
7.	Accessibility or Usability of the User Interfaces for Visually Impaired Users? A Comparative Study.	Accessibility
8.	Accessibility and Usability Problems Encountered on Websites and Applications in Mobile Devices by Blind and Normal-Vision Users.	Accessibility
9.	Preliminary Evaluation of Interactive Search Engine Interface for Visually Impaired Users.	Accessibility
10.	Accessibility Challenges of Hybrid Mobile Applications.	Accessibility
11.	Evaluation of touchscreen assistive technology for visually disabled users.	Assistive Devices
12.	Interactive sonification of U-depth images in a navigation aid for the visually impaired.	Assistive Devices
13.	UniPass: design and evaluation of a smart device-based password manager for visually impaired users.	Assistive Devices
14.	The Effect of the Usage of Computer-Based Assistive Devices on the Functioning and Quality of Life of Individuals who are Blind or have low Vision.	Assistive Devices
15.	A survey of assistive technologies and applications for blind users on mobile platforms: a review and foundation for research.	Assistive Devices
16.	An insight into smartphone-based assistive solutions for visually impaired and blind people: issues, challenges and opportunities.	Assistive Devices
17.	OCR based facilitator for the visually challenged.	Assistive Devices
18.	The interaction experiences of visually impaired people with assistive technology: A case study of smartphones.	Assistive Devices

19.	Social Media Platforms for Low-Income Blind People in India.	Assistive Devices
20.	Understanding In-Situ Use of Commonly Available Navigation Technologies by People with Visual Impairments.	Assistive Devices
21.	A Survey on the Use of Mobile Applications for People who Are Visually Impaired.	Assistive Devices
22.	Smart Electronic Stick for Visually Impaired using Android Application and Google's Cloud Vision.	Assistive Devices
23.	Advances in implantable bionic devices for blindness: a review.	Assistive Devices
24.	An interactive math braille learning application to assist blind students in Bangladesh.	Daily Activities
25.	Usability evaluation of a mobile phone-based braille learning application 'mbraille.	Daily Activities
26.	Design and usability of a braille-based mobile audiogame environment.	Daily Activities
27.	SparshJa: A User-Centric Mobile Application Designed for Visually Impaired.	Daily Activities
28.	Do you like my outfit?: Cromnia, a mobile assistant for blind users.	Daily Activities
29.	Usability in the app Interface Designing for the Elderly with Low-Vision in Taiwan and Thailand.	Daily Activities
30.	Developing Apps for Visually Impaired People: Lessons Learned from Practice.	Daily Activities
31.	Design and development of a mobile app of drug information for people with visual impairment.	Daily Activities
32.	Assessing Inconspicuous Smartphone Authentication for Blind People.	Daily Activities
33.	LˆeRˊotulos: A Mobile Application Based on Text Recognition in Images to Assist Visually Impaired People.	Daily Activities
34.	Getting Smartphones to Talkback: Understanding the Smartphone Adoption Process of Blind Users.	Daily Activities
35.	Evaluating Smartphone Screen Divisions for Designing Blind-Friendly Touch-Based Interfaces.	Screen Division Layout
36.	Blind-friendly user interfaces–a pilot study on improving the accessibility of touchscreen interfaces.	Screen Division Layout
37.	Accessible touchscreen technology for people with visual impairments: a survey.	Screen Division Layout
38.	Touchscreen-based haptic information access for assisting blind and visually-impaired users: Perceptual parameters and design guidelines.	Screen Division Layout
39.	Accessible Question Types on a Touch-Screen Device: The Case of a Mobile Game App for Blind People.	Screen Division Layout

40.	Touchscreen Based Text-Entry for Visually-Impaired Users.	Screen Division Layout
41.	An evaluation of SingleTapBraille keyboard: a text entry method that utilizes braille patterns on touchscreen devices.	Screen Division Layout
42.	A touch-sensitive keypad layout for improved usability of smartphones for the blind and visually impaired persons.	Screen Division Layout
43.	BraillePassword: accessible web authentication technique on touchscreen devices.	Screen Division Layout
44.	An evaluation of the brailleenter keyboard: An input method based on braille patterns for touchscreen devices.	Gestures
45.	Analyzing visually impaired people's touch gestures on smartphones.	Gestures
46.	Evaluation of touchscreen assistive technology for visually disabled users.	Gestures
47.	Improving reverse geocoding: Localization of blind pedestrians using conversational UI.	Audio Guidance
48.	Mobile Audio Games Accessibility Evaluation for Users Who Are Blind.	Audio Guidance
49.	Blind Reader: An intelligent assistant for blind.	Audio Guidance
50.	Audio Description of Videos for People with Visual Disabilities.	Audio Guidance
51.	Ebsar: Indoor guidance for the visually impaired," Computers & Electrical Engineering.	Navigation
52.	ASSIST: Evaluating the usability and performance of an indoor navigation assistant for blind and visually impaired people.	Navigation
53.	Usability evaluation of a mobile navigation application for blind users.	Navigation
54.	Touch Explorer: Exploring Digital Maps for Visually Impaired People.	Navigation
55.	Emotion enabled assistive tool to enhance dyadic conversation for the blind	Navigation
56.	Sightless Helper: An Interactive Mobile Application for Blind Assistance and Safe Navigation.	Navigation
57.	Using a mobile application to help visually impaired individuals explore the outdoors.	Navigation
58.	STAVI: Smart Travelling Application for the Visually Impaired.	Navigation
59.	PLACES: A Framework for Supporting Blind and Partially Sighted People in Outdoor Leisure Activities.	Navigation
60.	Qualitative measures for evaluation of navigation applications for visually impaired.	Navigation

Figure 1

Percentages of classification themes
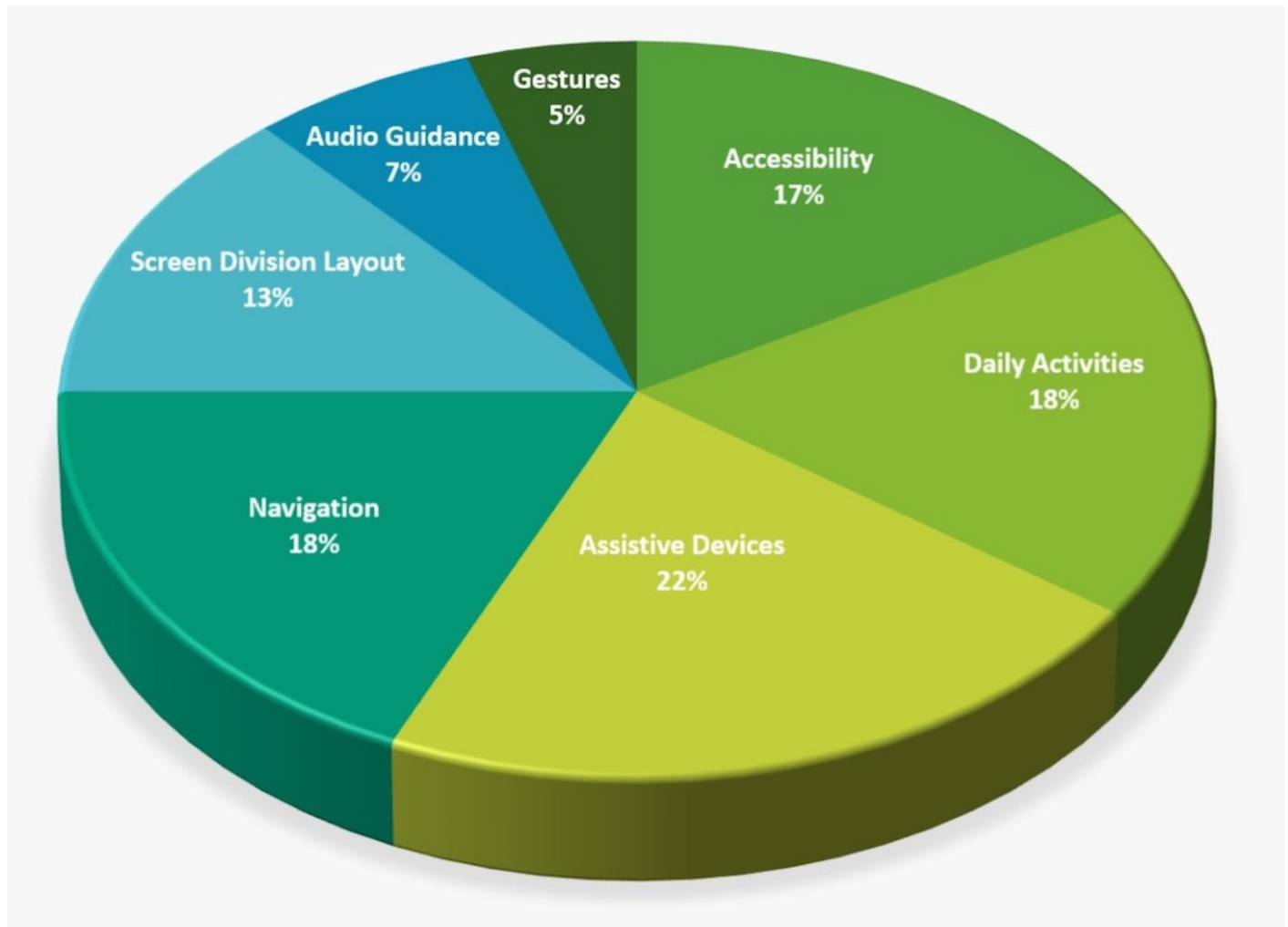
Figure 2

NAILS output sample
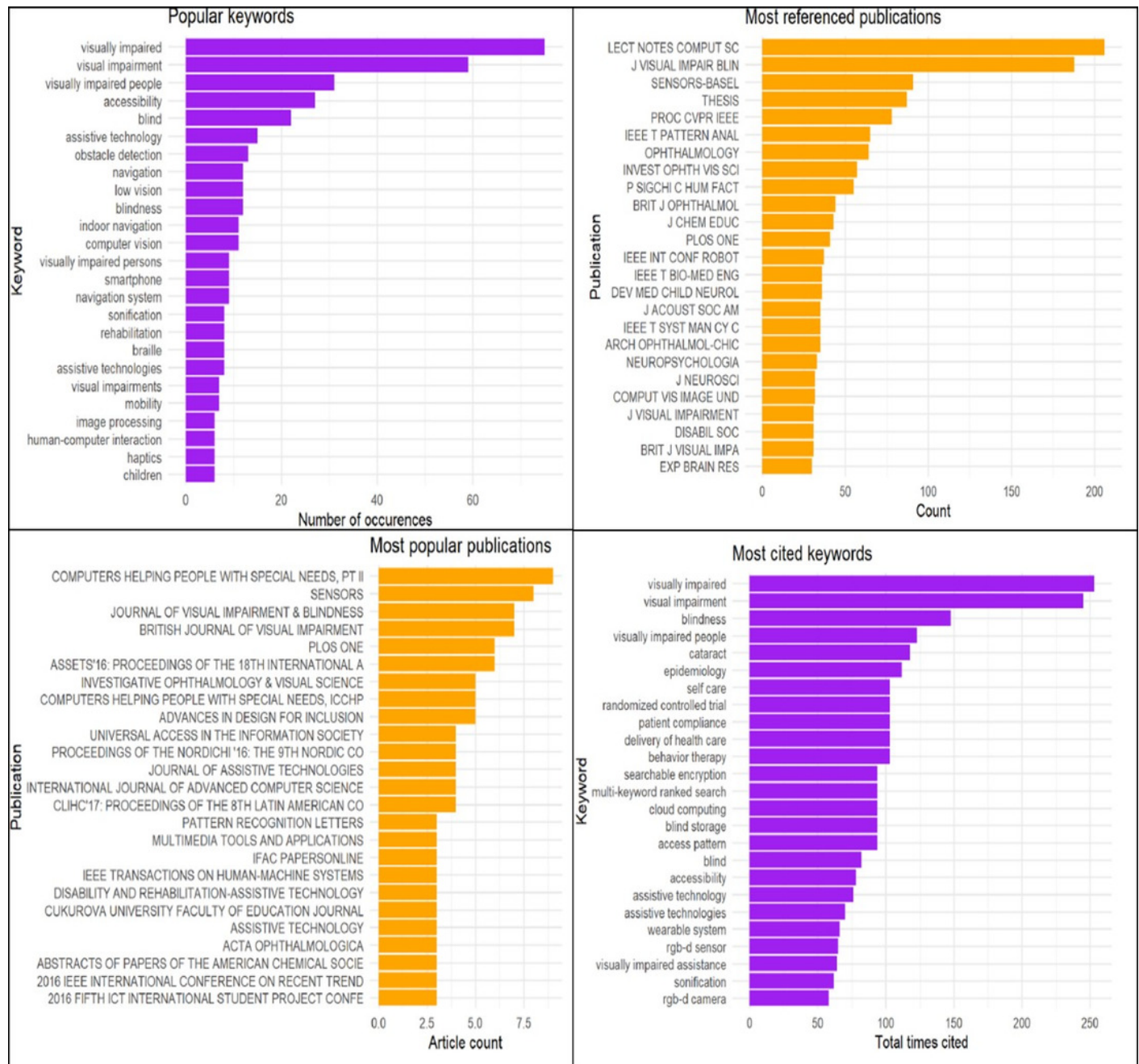
Figure 3

Number of papers per database
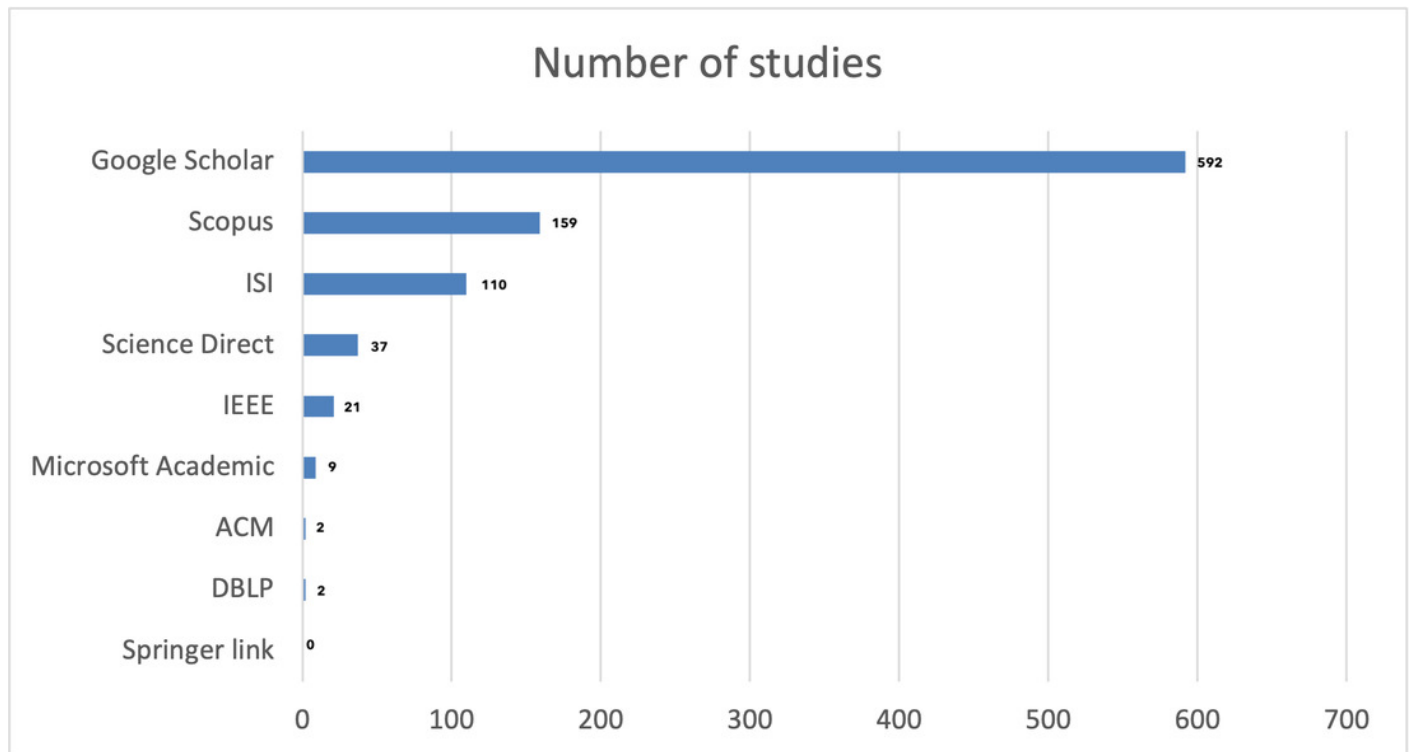
Figure 4

Search stages
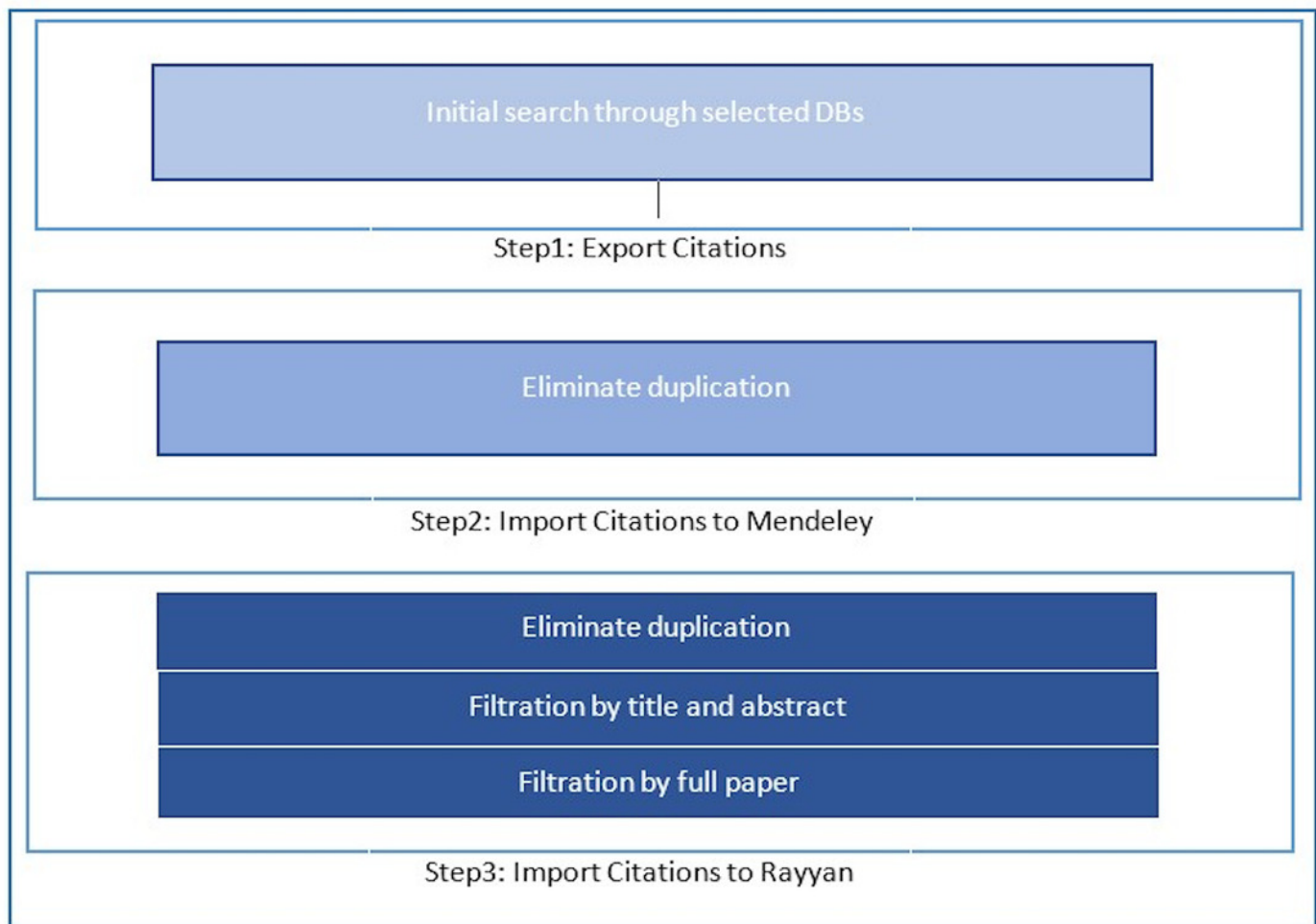
Figure 5

Quality assessment process
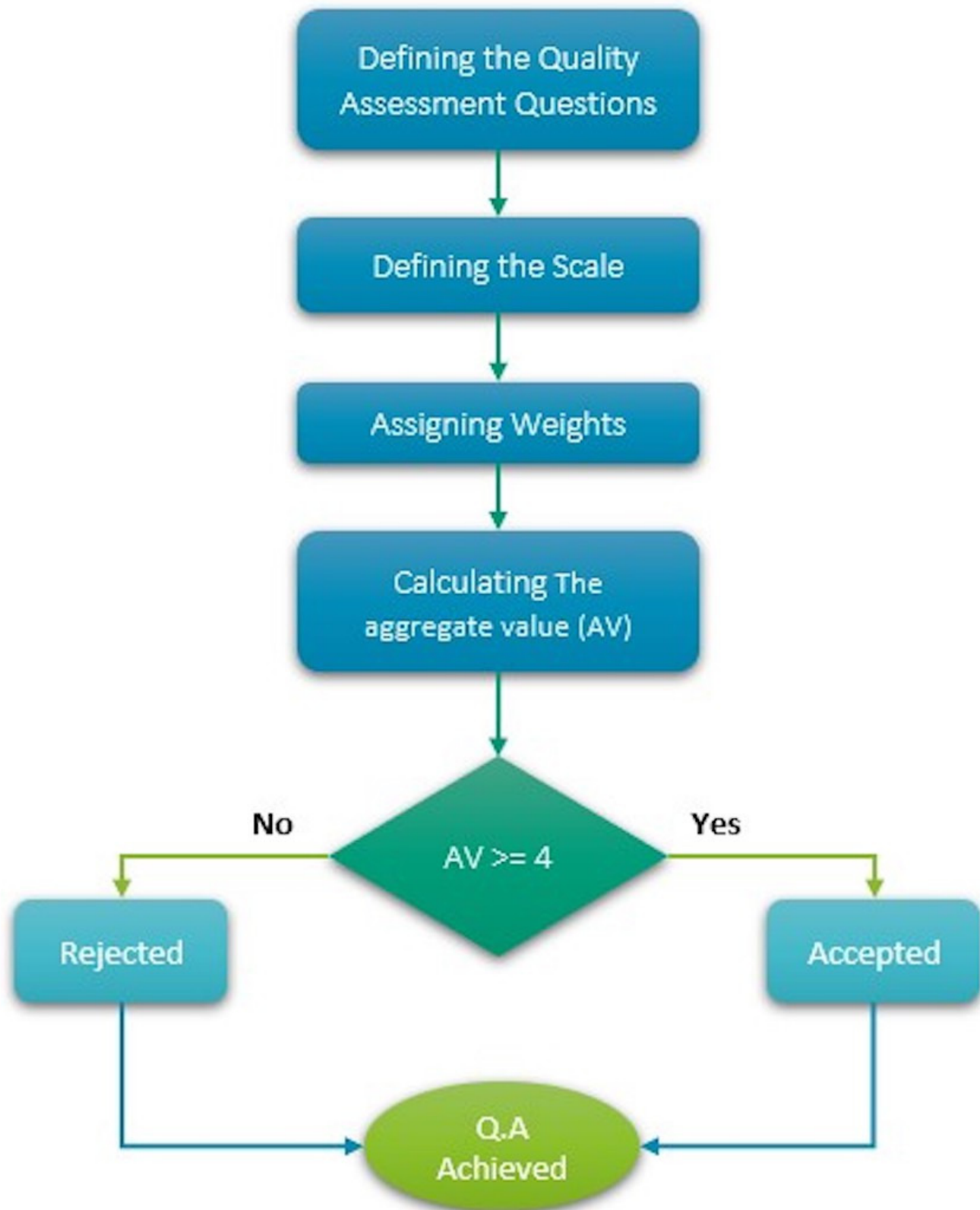
Figure 6

PRISMA flow diagram
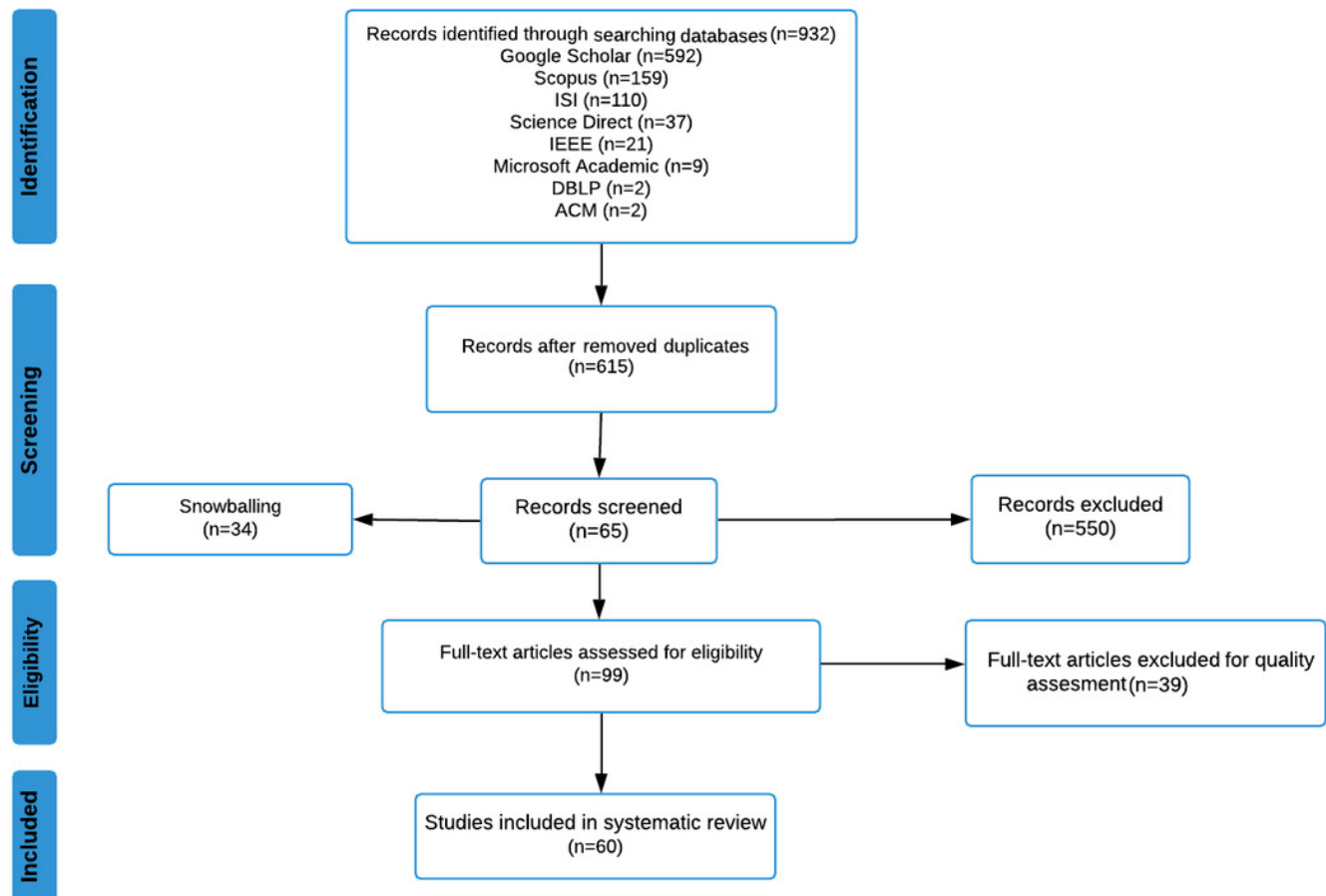
Figure 7

Results of the SLR
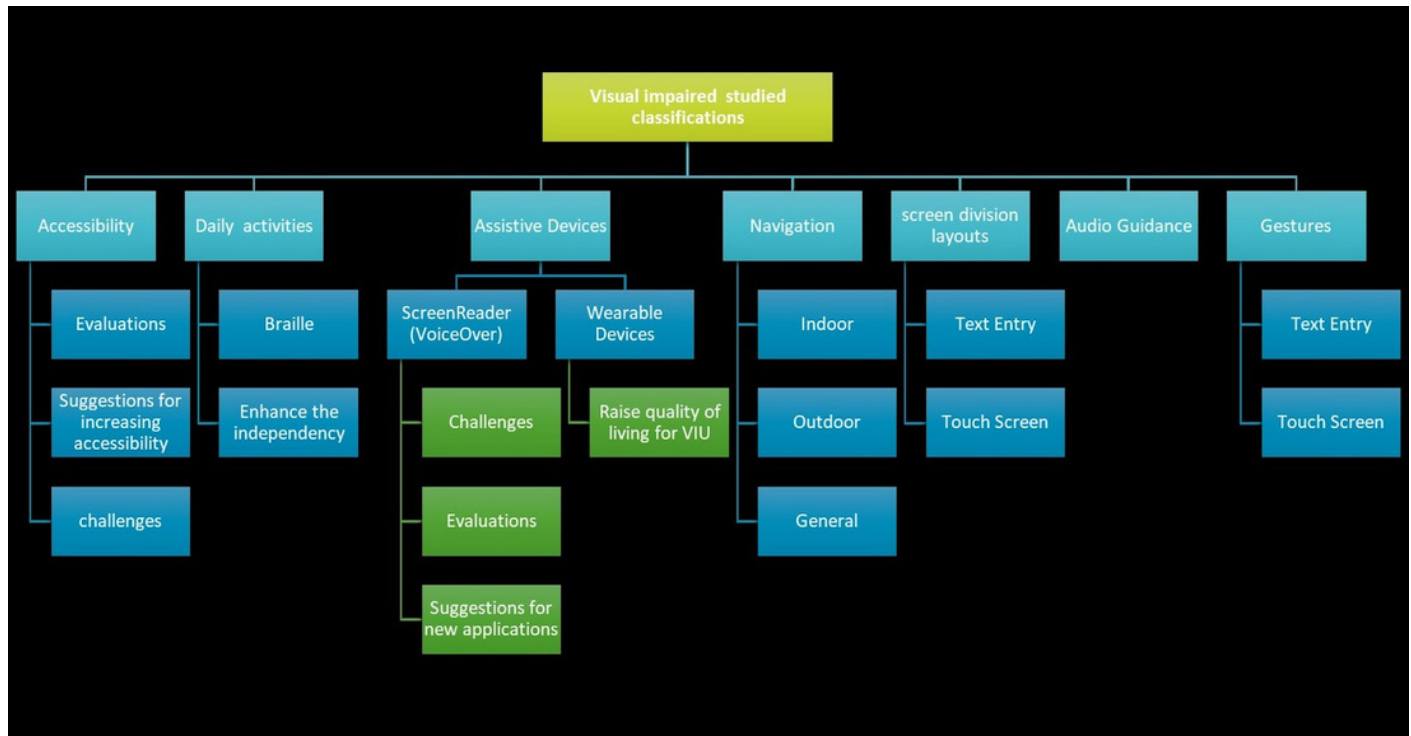
Figure 8

Publication trends over time

Figure 9

Outcomes of studies