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Mapping 20 years of accessibility research in HCI: A co-word analysis

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ABSTRACT

We employ hierarchical clustering, strategic diagrams, and network core–periphery analysis to assess and visualise the intellectual progress of accessibility research within HCI in the past two decades. The study quantifies and explains the development of accessibility research and its thematic evolution based on 1,535 papers published at TACCESS, ASSETS, IJHCS, and CHI and their respective 3,470 author-assigned keywords. The novelty of this work is based on employing a quantitative methodological approach to provide an overview of accessibility research progress and insights into its driving and trending themes through the period 2001–2021. In addition, we identify declining, emerging, and core backbone themes of accessibility research. Finally, we discuss the opportunities for research that arise from our findings. These contributions provide a roadmap for researchers working on accessibility.

1. Introduction

Accessibility has long been an important area in Human–Computer Interaction (HCI), and has been described as one of the few areas in which HCI has extensively influenced public policy (Lazar et al., 2016). Accessibility research is inherently interdisciplinary, bringing together Computer Science, Health and Medical Sciences, Rehabilitation Engineering, Psychology, and many others. Given this multidisciplinary focus and the ever-increasing technological possibilities, accessibility is continuously evolving as a research area. In this paper, we reflect on past, present, and developing trends within accessibility research to better understand its evolving scope, and to recognise future opportunities in this domain. Our analysis enables us to identify core topics, detect under-developed themes, and map out their contributions to the field, thereby guiding researchers, designers, and developers in their accessibility-related work.

In particular, we employ co-word analysis (Cambrosio et al., 1993) to provide insights into the developments of accessibility research as a prominent research area within HCI. Co-word analysis explores associations and connections between concepts that contribute to the development of a research area or field. The method assumes that keywords provide a sufficient synopsis of a research article—keywords can then be used to examine connections between research concepts. Another assumption of co-word analysis is that the co-occurrence of keywords in different articles indicates a connection between these articles that may embody a research theme (Cambrosio et al., 1993; Hu et al., 2013; Liu et al., 2014b). Previous works have used co-word analysis to study ubiquitous computing (Liu et al., 2014a), child–computer interaction (Giannakos et al., 2020), and the CHI community (Liu et al., 2014b). These analyses have enabled a reflection on the contributions of these respective fields, highlighting both shortcomings and opportunities.

We present a study that provides an overview and reflection of the intellectual progress in accessibility research within HCI for the past two decades: 2001–2010 and 2011–2020. We analyse papers published at the four main venues in HCI research with a focus on accessibility: the ACM Conference on Accessible Computing (ASSETS), ACM Transactions on Accessible Computing (TACCESS), the International Journal for Human–Computer Studies (IJHCS), and the ACM Conference on Human Factors in Computing Systems (CHI). ASSETS and TACCESS are the primary publication venues for accessibility research; whereas the CHI conference and IJHCS are considered premier venues in HCI, and thereby provide an inclusive representation of the Human–Computer Interaction landscape (Hornbæk et al., 2019). As such, our investigation is focused solely on HCI-related aspects of accessibility research.

Our contribution is three-fold. First, we provide an overview of accessibility research progress from 2001 to 2020. We show that

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accessibility research has grown substantially in the past decade, and that there was a clear shift in research interests in the community over the past two decades. Second, we identify declining, emerging, and core backbone themes of accessibility research in the past two decades. In particular, we demonstrate how different topics have developed and shifted in popularity within this period. For example, we find that 'motor impairments' was a driving topic in decade 1; however, it was not any more in decade 2. Similarly, 'blind and visual impairments' was a weakly structured topic in the first decade but became a driving topic in the second decade of analysis. Finally, we discuss the opportunities for research that arise from our findings. For instance, we identify 'adaptive interfaces', 'affective computing', and 'education' as potential motor themes in accessibility research going forward. These contributions provide a roadmap for researchers and designers working on accessibility.

2. Related work

In this section, we provide an overview of accessibility research in HCI. Further, we give an outline of the co-word analysis methodology and how it was employed to analyse and understand intellectual progress in HCI.

2.1. Accessibility research in HCI

Mack et al. (2021) reviewed accessibility papers published at CHI in the period 2010–2019 and at ASSETS in the period 1994–2019. Their review characterises current trends in accessibility research, identifies areas that received disproportionate attention, and reports on used research methods. The authors determined that the most common research methods used in accessibility research were interviews, usability testing, and controlled experiments. The authors also found that the most common locations for conducting accessibility research were laboratory environments, but that there was also research involving other locations, such as participants' homes and community centres (Mack et al., 2021).

Further, the authors found that the majority of accessibility studies recruited participants with disabilities or older adults; depending on the study design and the type of work, non-disabled participants were also involved (*e.g.*, caregivers and other stakeholders). Notably, the authors found that accessibility research had proliferated within the last five years, making up almost 8% of published papers at CHI in 2019. In terms of trend development in accessibility research, the authors identified that the main focus of research is directed to the blind and visually impaired communities, followed by the motor/physically impaired and the deaf or hard of hearing communities. Similarly, older adults and cognitively impaired communities appear consistently in accessibility research, starting from the early years. Recently, topics such as autism, neurodiversity, and mental health have attracted increasing attention from HCI researchers (Mack et al., 2021).

In terms of technological advancement, games, wearable computing, social computing, 3D printing, DIY, AR/MR/VR, and collaboration tools have become commonplace in the past ten years. Meanwhile, research on mobile and web technology has plateaued in the past decade. Finally, in terms of methodological practices, the authors suspect a general lack of keywords related to research methodology in accessibility papers. Nevertheless, the authors observed that usability dropped over time, whereas user experience (UX) gained popularity from 2005 to 2010 together with interviews (Mack et al., 2021).

In contrast to Mack et al. (2021), rather than examining research trends, Abbott et al. (2019) analysed papers published at CHI to assess the field's local standards for anonymisation practices in wellness, accessibility, and ageing research. The authors reviewed 509 manuscripts published at CHI between 2010 and 2018. In their work, the authors identify the most common categories of participants' diagnoses, with visual impairments leading the list, followed by autism, mental health, dementia, cancer, motor impairments, diabetes, Parkinson disease, chronic pain, and hearing impairments. The authors also assessed sample size standards, privacy, and information disclosure. The authors found that the open publishing of research data is low, and replication is non-existent in the CHI health literature. The findings of this work provide concrete suggestions for research directions and methods in the HCI community, explicitly pointing at reporting ethical aspects of human-subject research and guidelines for avoiding privacy risks, *e.g.*, potential re-identification of participants (Abbott et al., 2019).

There have also been several works surveying specific topics within accessibility. For example, Li and Flatla (2019) review 30 years of Colour Vision Deficiency (CVD) research. The authors employed a Persona Driven Inquiry method to survey academic literature in the field and assess whether the findings of CVD research are available to the general public. The authors also identify opportunities for academics to increase their scholarly impact by improving different accessibility measures of online tools (Li and Flatla, 2019). Andrew et al. (2020) surveyed accessibility work related to authentication techniques. Following a categorisation of authentication techniques by different impairment types (*e.g.*, blind and low vision, deaf and hard of hearing), the authors provide recommendations for future work based on the identified research gaps for each category. For example, Andrew et al. (2020) point to the need for more qualitative studies to understand the concerns of deaf or hard of hearing users during authentication. Other sub-areas examined by accessibility scholars are autism (Lorah et al., 2015; Pennisi et al., 2016; Spiel et al., 2019), designing with older adults (Vines et al., 2015), and visual accessibility (Bhowmick and Hazarika, 2017; Brulé et al., 2020; Grussenmeyer and Folmer, 2017).

In contrast to existing surveys of accessibility research (Abbott et al., 2019; Mack et al., 2021), our work follows a highly structured co-word analysis-driven approach in analysing the literature to derive the development and the progress of the entire area of accessibility within HCI research. To be precise, co-word analysis enables us to identify key patterns and trends indicating particular changes in research topics or a change in research direction. We further extend previous work (Mack et al., 2021) by including papers published not only at CHI and ASSETS, but also TACCESS as the premiere journal within HCI on accessibility and IJHCS as a broad journal within HCI. Furthermore, the major difference of our work compared to prior research conducted by Mack et al. (2021) is constituted in employing a quantitative approach to provide an intellectual progress of accessibility research in HCI. Our work is based on hierarchical clustering of author keywords and understanding the relationships between these keywords to describe the progress of accessibility research. Furthermore, we provide an overview of accessibility research in HCI for the period of 20 years and investigate the shift in research paradigms between the two decades: 2001–2010 and 2011–2020. Hence, our work gives a comprehensive understanding of how research interests have changed within these two decades. Therefore, not only does our work complement prior research by Mack et al. (2021) by adding quantitative evidence to previously reported findings, it also contributes new knowledge as we identify declining, emerging, and core backbone themes of accessibility research in the past two decades and forecast future trends for accessibility research in the next decade.

2.2. Co-word analysis

Co-word analysis is widely used to analyse textual content. It focuses on understanding the relationship between terms in a text, and is used for mapping patterns and trends of associated words (Callon et al., 1983). Given these features, co-word analysis offers a powerful bibliometric approach to map the evolution and assess the structure of scientific disciplines using publication data, including metadata, titles, abstracts, and keywords. Ideally, keywords are used to describe the content of a research article (Giannakos et al., 2020). Thus, co-word analyses of keywords can reveal the conceptual structure and evolution

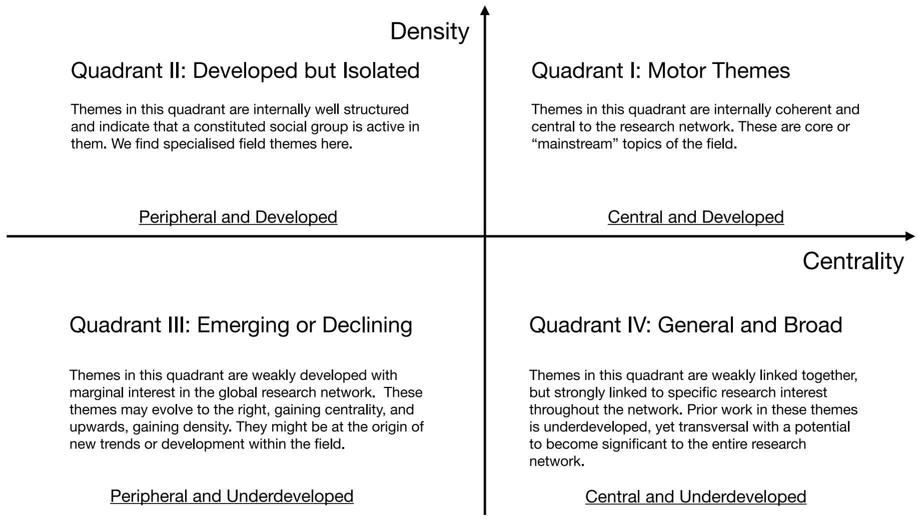


Fig. 1. Strategic diagram of density and centrality.

of the research topics within the area or field in focus, based on the interaction of the respective keywords (Giannakos et al., 2020). The basic idea behind this type of analysis is that if two keywords appear together within one paper, the research topics represented by these keywords are more likely to be related. Further, higher co-word frequency suggests a stronger correlation in keyword pairs, thus implying that the two keywords are associated with a specific research theme (Cambrosio et al., 1993).

Technically, co-word analysis reduces a broad network of keywords to smaller networks of closely related keywords using graph theory (Cobo et al., 2011). These graphs have nodes and edges, represented with keywords links between the nodes respectively. To define a conceptual structure and the characteristics of a research area or field, we use keyword networks and clusters of keywords. Clusters of keywords that appear together in papers are also called research themes. In this study, we use two standard measures from graph theory in our analysis: *density* and *centrality*.

- Density – describes the proportion of direct connections between the nodes to the total possible connections within a network. Density aims to quantify the prevalence of dyadic connections within a network, which can explain interaction between the nodes (Callon et al., 1991).
- Centrality – the degree of interaction of the node (theme) with other nodes of the network. Centrality aims to quantify the "importance" and "influence" of a particular node within a network (Callon et al., 1991).

Thus, density describes the internal cohesion of the theme, measuring the strength of the links that hold the cluster of keywords that create a theme together. In other words, a high density implies that the cluster is more coherent; hence it is more likely to contain inseparable expressions (Liu et al., 2014b). Centrality describes the importance of a research theme in the development of a research area or field, as it measures the relation of a research theme to other topics within the network (Callon et al., 1991). The stronger a cluster is linked to the network of themes, the more central it becomes to the whole network. Clusters of keywords can be positioned on a 2-dimensional strategic diagram, as presented in Fig. 1. Strategic diagrams have centrality as their x-axis and density as their y-axis.

Conceptually, strategic diagrams are divided into four quadrants. A theme's position in the quadrant describes its development and intellectual progress within the research area or field. *Quadrant I* contains themes with **high centrality** and **high density** values. These themes are internally coherent and have strong links to the research network; this implies that these are motor ('mainstream') themes within the network (Callon et al., 1991). *Quadrant II* includes themes with **high density** and **low centrality**, meaning that these themes are internally coherent, but have insignificant external ties (Callon et al., 1991). In other words, these themes are more specialised and peripheral to mainstream research work. *Quadrant III* holds themes with **low centrality** and **low density** values, implying that these themes are neither internally coherent nor have strong links to the rest of the network. Usually, Quadrant III holds either emerging or disappearing research themes (Callon et al., 1991). Finally, *Quadrant IV* contains themes with **low density** but **high centrality**. Usually, the topics in this quadrant are weakly structured and underdeveloped; however, they have strong links to the entire network. These themes have the potential to gain considerable significance within the entire research network. They can potentially influence the development of all the other themes, as they are central to the entire network (Callon et al., 1991; Liu et al., 2014b; Muñoz-Leiva et al., 2012).

To summarise, co-word analysis is used to understand the connection of research topics, the development of a research area or field as a whole, and to trace changes in research interest within the conceptual spaces of a specific research area or field. Co-word analysis has previously been shown to effectively reveal patterns and trends of different research disciplines (Ding et al., 2001) and has been widely used to assess the intellectual progress of HCI research (Liu et al., 2014b,a; Giannakos et al., 2020).

2.3. Co-word analysis in HCI

Liu et al. (2014b) used co-word analysis to understand and visualise the intellectual progress of the CHI conference for two decades between 1994 and 2013. The authors analysed 16,035 keywords from 3,152 papers and identified an evolution of major themes as well as popular, core, and backbone research topics within HCI. Findings from their analysis show how novel research directions, subsequently followed by new conferences (*e.g.*, IUI, Ubicomp), have emerged from the mainstream themes in the first decade between 1994–2003. The authors also demonstrate that HCI research experienced a paradigm change between 2004–2014, with almost half of the popular topics identified in the first decade being replaced by new research topics. Further, the authors show that over time HCI has become more cohesive as the keywords' centrality and density increased in the second decade as compared to the first decade (Liu et al., 2014b). Finally, the results of the study by Liu et al. (2014b) demonstrate that the field of HCI is gradually maturing in terms of its themes, but more can be done to accumulate knowledge and build theory.

In their follow-up work, Liu et al. (2014a) used co-word analysis to examine the development of the Ubicomp research field based on the keywords extracted from papers published at Ubicomp—ACM International Joint Conference on Pervasive and Ubiquitous Computing—in the period between 1999 and 2013. The authors used keywords, networks, and clusters to provide an overview of the progression of Ubicomp research, as well as the density and centrality of the field to measure the development of the research themes and their importance within Ubicomp research (Liu et al., 2014a). The authors demonstrate that the field of Ubicomp experienced explosive growth between 1999 and 2013. The authors further show that Ubicomp research has become inherently more cohesive with time. Additionally, the authors identify emerging, mainstream, and fading research themes in the Ubicomp community for the given period. Finally, based on their findings, the authors predict the future of Ubicomp research and refute that Ubicomp is facing an identity crisis (Abowd, 2012; Liu et al., 2014a). Similar to Liu et al. (2014a,b), Lee et al. (2019) analysed the citation network of papers published at CHI and identified long-term research trends based on keyword analysis. The authors argue that keyword analysis can be used to establish subcommittees to support emerging research themes at the CHI conference.

Co-word analysis has also been used to analyse the development of games research (Melcer et al., 2015). Melcer et al. (2015) used metadata of the collected publications in their study to conduct co-word analysis. The authors identified 20 research themes and communities for these themes in games research. Their work outlines publication strategies for researchers and provides suggestions for choosing the right publication venue, particularly for inexperienced early career researchers (Melcer et al., 2015). Similarly, Giannakos et al. (2020) mapped Child–Computer Interaction (CCI) research using co-word analysis. The authors analysed keywords from scientific articles published at the Interaction Design and Children conference and in the International Journal of Child–Computer Interaction in 2003–2018. Through the analysis of 1,059 articles, the authors identified motor themes, topics of marginal interest, and topics that can potentially gain significant importance within Child–Computer Interaction research (Giannakos et al., 2020). With their findings, the authors demonstrate the steady growth and maturation of CCI research. The authors also show that the CCI community has a healthy distribution of research topics, with several motor themes (*e.g.*, coding, education, play, child robot interaction). The authors further show that the community also engages with emerging underdeveloped topics (*e.g.*, tablets, parents, e-books). Finally, the authors suggest that publications in the CCI community should include keywords describing the targeted age group and used methodologies to produce highly generative knowledge demonstrating a transfer of knowledge between age groups (Giannakos et al., 2020).

Co-word analysis is not the only method that analyses bibliographic metadata to make inferences about the state-of-the-art of a research area or field. For example, in contrast to the works mentioned above, Völkel et al. (2020) use only the key term 'intelligent' to analyse 1,111 papers published at the International Conference on Intelligent User Interfaces (IUI) over a period of 25 years. The authors investigated the co-occurrence of this keyword with other descriptions to draw an implicit understanding of the term from the researcher's perspective (Völkel et al., 2020). The authors did not employ co-word analysis in their work, but they manually mapped the key term to entities, co-descriptors, and actions identified in the papers. Similarly, Hornbæk et al. (2019) analysed the meaning and the use of the key term 'interaction' in 5,349 manuscripts published at CHI between 1981–2016, demonstrating a growing diversity in the characterisation of the term. Hornbæk et al. (2019) employed natural language processing techniques to first extract sentences in which the keyword was used, then extract noun phrases and n-grams, and subsequently map them to the key term.

Another common approach to analyse a research area or field is bibliometric analysis, which has been widely used to analyse and provide an overview of HCI research (Mannocci et al., 2019). For example, Mannocci et al. (2019) examined manuscripts published in the International Journal of Human–Computer Studies (IJHCS) since 1969 and manuscripts published at CHI since 1982. The authors analysed bibliographic metadata of these publications and identified geopolitical patterns and emerging key trends (Mannocci et al., 2019). Similarly, Wang et al. (2021) employed bibliometric analysis of the reference citations in accessibility papers within HCI research. The authors examined publications from 13 accessibility and HCI venues. They identified citation patterns of accessibility research, its relation to other fields of Computer Science, and the evolution and patterns of research trends (Wang et al., 2021).

In sum, co-word analysis has been successfully used to identify conceptual structures of several research areas and fields, and the development of research trends. In this paper, we employ co-word analysis to understand the progress, development, and maturation of accessibility research in HCI. We analyse keywords extracted from papers published at CHI, ASSETS, IJHCS, and TACCESS, and follow the analysis approach previously presented in Liu et al. (2014a,b), Giannakos et al. (2020).

3. Method

To obtain a corpus of relevant papers for our analysis, we queried the ACM Digital Library and Scopus for papers published between 2001 and 2020. Our search was restricted to the two main publication venues for HCI-focused Accessibility research—*The ACM Conference on Accessible Computing (ASSETS)*, *The ACM Transactions on Accessible Computing (TACCESS)*—and two broader HCI publication venues—*The ACM Conference on Human Factors in Computing Systems (CHI)* and the International Journal of Human–Computer Studies (IJHCS). We considered *all papers* published at both ASSETS and TACCESS, as those venues focus purely on accessibility research (Mack et al., 2021). However, we filtered the papers published at CHI and IJHCS to identify those focused on accessibility. International Conference on Computers Helping People with Special Needs. Rather than aiming to include all venues with an interest in accessibility, we deliberately limited the scope of our investigation to the field of Human–Computer Interaction We followed the filtering approach introduced by Mack et al. (2021), and considered papers with the following keywords in the title, abstract, or author keywords: *disab** (*e.g.*, disability), *accessib** (*e.g.*, accessibility, accessible), and *impair** (*e.g.*, impairment, impaired). We selected these keywords because they represent a sufficiently wide range of accessibility papers, and help us avoid potential bias that could occur if specific keywords were selected, such as 'assistive tech', 'blind', or 'deaf'. We relied on ACM DL advanced search to match the aforementioned search criteria. Returned results were exported in a separate spreadsheet file (.csv) for further analysis.

Our search query returned 1,535 papers from ASSETS, 206 papers from TACCESS, 1,057 papers from the CHI proceedings, and 93 papers published at IJHCS. We limited our dataset to research articles only, *i.e.*, we removed extended abstracts, posters, and keynotes. Following this, our dataset consisted of 734 papers published in ASSETS, 175 papers published at TACCESS, 494 papers published at CHI, and 93 papers published at IJHCS. Lastly, we removed papers that did not have any author keywords (28 papers). We split the final dataset into two decades: *Decade 1* contained papers 419 papers published in the time period of 2001–2010 and *Decade 2* contained 932 papers published in the period of 2011–2020.

We extracted all author keywords (N = 3470 keywords) from the papers, and manually revised and grouped them under a unified overarching common keyword, *e.g.*, keywords *'blind and vision impaired'*, *'blind and visual impairment'*, *'blind children'*, *'blind people'*, *'blind persons'*, *'blind or visually impaired'* were grouped into *'blind or visually impaired'*. Keywords appearing in singular and plural form, gerunds, abbreviations, and acronyms were also merged. We further removed generic and non-descriptive keywords when analysing our dataset, *e.g.*, 'accessibility', 'accessible technology', and 'hci'. Please refer to the supplementary materials for a complete list of original keywords and how they were grouped. Four of the paper's authors manually and collaboratively scanned through the keywords and grouped the keywords, resulting in a total of 242 unique keywords used in our analysis.

The frequency of keywords follows a power-law distribution (α = 3.08, $R^2 = 0.54$). Networks with a power-law distribution are asymptotically 'scale-free'. The most notable characteristic of scale-free networks is that they contain some nodes (called 'hubs') with many more connections than other vertices. The landscape of accessibility research is a scale-free network, with a number of high frequency keywords that act as hubs and are linked to different topics. These keywords capture major research directions of this research area and outline its intellectual structure (Giannakos et al., 2020; Wang et al., 2012). Another major characteristic of a scale-free network is that the major research themes of the intellectual network can be defined with a small subset of hubs. For example, a previous analysis of the CHI conference proceedings between 1994–2013 (20 years, 3152 articles) showed that less than 100 keywords were sufficient to describe an intellectual field comprehensively (Assefa and Rorissa, 2013; Liu et al., 2014a,b).

Based on the power-law analysis, the minimum keyword frequency was $n = 9$ for Decade 1, and $n = 30$ for Decade 2. Therefore, we retained keywords that co-occurred more than 9 times in the first decade and more than 30 times in the second decade. Thus, we selected a total of 91 keywords for the period of 2001–2010, and 76 keywords for the period of 2011–2020. Hence, for Decade 1, we covered 400 of the 419 published articles, *i.e.*, 95% of the papers are represented by at least one of these keywords in the final dataset. Similarly, for Decade 2, we covered 915 of 932 papers, *i.e.*, 98% of publications are represented by at least one of the keywords in the final dataset. We followed the same methodology reported in previous works focusing on HCI (Liu et al., 2014b), ubiquitous computing (Liu et al., 2014a), child computer interaction (Giannakos et al., 2020), and digital games (Melcer et al., 2015).

4. Results

Due to the increasing popularity of accessibility as a research area, our dataset included significantly more papers published in the second decade (2011–2020) than in the first (2001–2010) (see Fig. 2). The number of accessibility papers published at HCI venues has grown substantially throughout this period, indicating an increased interest in accessibility research among HCI scholars. Fig. 2 shows that ASSETS initially ran biennially and became an annual conference starting in 2004, while TACCESS began publishing in 2008, its founding year.

4.1. Analysis of strategic diagrams

To identify major research themes in accessibility, we conducted a cluster analysis using hierarchical clustering with Ward's method and 'Squared Euclidean distance' for distance measures for both decades (Ward, 1963). This supervised clustering method accounts for content validity and fitness of cluster size (Giannakos et al., 2020). To define the optimal number of clusters, we used the Gap Statistics method (Tibshirani et al., 2001).

4.1.1. Decade 1: 2001–2010

The final set of 91 keywords for Decade 1 was divided into nine clusters. We named these clusters C1 to C9 accordingly, which are summarised in Table 1 and visualised in the strategic diagram presented in Fig. 3(a). From Fig. 3(a) we can derive that Quadrant I (Q1, top-right) of the strategic diagram holds clusters C2 and C5. Q1 contains keywords with high centrality and high density values, indicating that they are the motor themes in Decade 1. According to our results, keywords from cluster C2 (*e.g.*, 'motor impairments', 'input devices, 'cursor', 'explicit interaction', 'submovements', 'gestures', 'text entry and manipulation', 'touch', 'target acquisition', and 'Fitts' law) and keywords from cluster C5 (*e.g.*, 'cognitive impairments', 'mobile', 'design', 'co-design', 'qualitative research', 'wayfinding', 'in-the-wild', 'security', 'quality of life', 'technology') were the driving accessibility themes in Decade 1.

Quadrant II of Fig. 3(a) contains cluster C1, C3, and C4. These clusters hold topics with high centrality but low density values, indicating that the themes in this quadrant are well-structured internally and demonstrate that a constituted social group is actively developing these topics. In particular, Quadrant II of Fig. 3(a) contains such keywords as 'cyber technology' (C1), 'deaf or hard of hearing' (C1), 'sign language' (C1), 'animation' (C1), 'quantitative research' (C1), 'natural language processing' (C1), 'motion' (C1), 'art' (C3), 'drawing' (C3), 'eye interaction' (C3), 'input' (C3), 'youth' (C3), 'social' (C4), 'collaborative' (C4), and 'metadata' (C4).

Quadrant III of Fig. 3(a) contains clusters C7 and C8. Quadrant III indicates that the topics are weakly developed in the global research network with low density and low centrality. Topics in this quadrant are mainly the themes that are either emerging or disappearing. According to our results the keywords in Quadrant III are the following: 'spatial' (C7), 'image processing' (C7), 'affective computing' (C7), 'braille' (C7), 'artificial intelligence' (C7), 'tactile' (C7), 'detection' (C7), performance (C8), 'wearables' (C8), and 'smart textiles' (C8).

Finally, Quadrant IV of Fig. 3(a) contains clusters C6 and C9. Quadrant IV presents weakly structured themes strongly linked to specific research interests throughout the network. Usually, prior work in these themes is underdeveloped yet transversal, hence, the theme can gain considerable significance within the entire research network. Details of these clusters and corresponding keywords can be found in Table 2.

4.1.2. Decade 2: 2011–2020

We divided the final set of 76 keywords for Decade 2 into eight clusters. We named these clusters as C1 to C8 accordingly and summarised them in Table 2. We visualised the clusters in strategic diagrams as shown in Fig. 3(b).

Fig. 3(b) shows that Quadrant I contains clusters C2 and C6; hence, indicating that the keywords from these two clusters are the motor themes of accessibility research in Decade 2. These clusters contain such keywords as 'blind and visually impaired' (C2), 'navigation' (C2), wayfinding (C2), 'auditory' (C6), 'web' (C6), 'text entry and manipulation' (C6), 'reading' (C6), and 'eye interaction' (C6).

Furthermore, Fig. 3(b) shows that cluster C4 is located in Quadrant II of the strategic graph for Decade 2. Such keywords as: 'deaf or hard of hearing (DHH)' (C4), 'sign language' (C4), 'captions' (C4), and 'feedback' (C4) have high centrality and low density values. Hence, it is an indication that these topics were developed but isolated during 2011–2020.

Quadrant III of Fig. 3(b) contains clusters C3 and C7 with such keywords as 'haptics', 'multimodal interaction', 'quantitative research', 'visualisation', 'explicit interaction', 'crowdsourcing', 'tactile', These topics have low density and low centrality values, and are either emerging or disappearing. Finally, from Fig. 3(b) we observe that Quadrant IV contains clusters 1, 5, and 8. These topics are weakly structured and are linked to specific research interests that might become significant for the entire research area. Details of these clusters and respective keywords are presented in Table 2.

4.2. Analysis of keyword networks

Next, we present a network analysis of the papers' keywords. When associations between keywords are formed, multiple keyword networks associated with different themes are created (Giannakos et al., 2020). A keyword network demonstrates the relationship among different research themes. In a network, keywords are represented by the nodes,

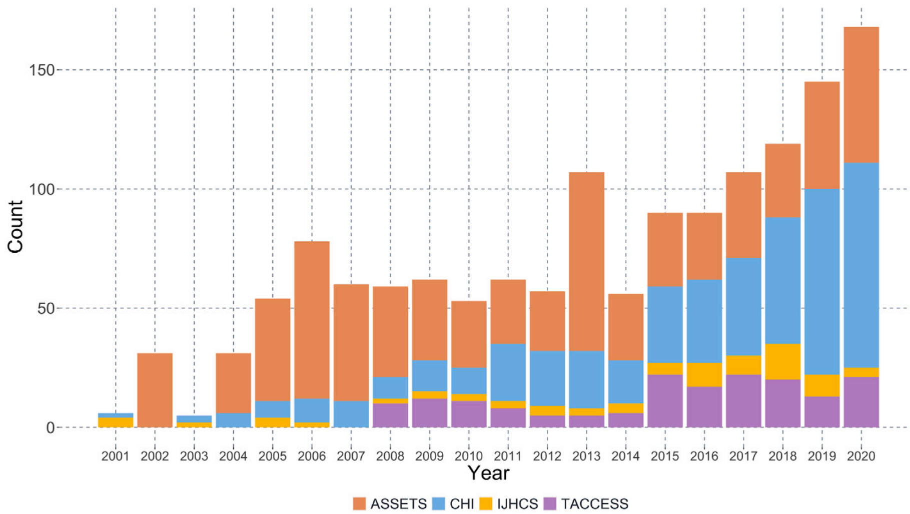
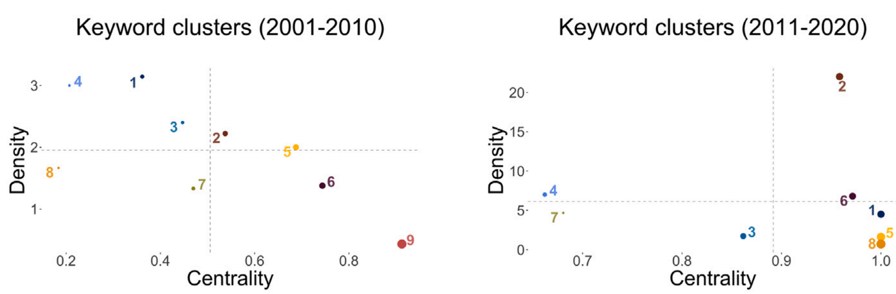


Fig. 2. Number of publications per year per venue.



(a) Strategic diagram for 2001–2010 (b) Strategic diagram for 2011–2020

Fig. 3. Overview of keyword clusters in the accessibility research field.

Table 1
Research Themes of 2001–2010: size, total frequency (TF), co-word frequency (CW-F), centrality (Centr.), density.

ID	Keywords (2001–2010)	Size	TF	CW-F	Centr.	Dens.
C1	Cyber technology, deaf or hard of hearing (DHH), sign language, animation, quantitative research, natural language processing, motion	7	68	197	0.36	3.14
C2	Motor impairments, input devices, cursor, explicit interaction, submovements, gestures, text entry and manipulation, touch, target acquisition, Fitts' law	10	129	373	0.54	2.22
C3	Art, drawing, eye interaction, input, youth	5	43	116	0.44	2.40
C4	Social, collaborative, metadata	3	19	51	0.21	3.00
C5	Cognitive impairments, mobile, design, co-design, qualitative research, wayfinding, in-the-wild, security, quality of life, technology	10	170	442	0.69	2.00
C6	Auditory, visualisation, programming, augmentative and alternative communication (AAC), interventions, nonverbal, autism, cognition, feedback, scanning, theory, video	12	190	498	0.75	1.38
C7	Spatial, image processing, affective computing, braille, artificial intelligence, tactile, detection	7	56	160	0.46	1.33
C8	Performance, wearables, smart textiles	3	15	35	0.18	1.67
C9	Blind and visually impaired (BVI), web, modelling, memory aid, navigation, nonvisual, sensing, school subject, adaptive interface, health, wheelchairs, haptics, multimodal interaction, personalisation, care, semantics, communication technology, documents, brain–computer interaction, therapy, education, older adults, tools, social interaction, information assembly, conversation, games, errors, reading, evaluation method, context, learning, inclusive	33	434	916	0.91	0.44

and are connected within the network through the links that allow communication and information flow between the nodes (Nielsen and Thomsen, 2011). Isolated regions within the network are known as *structural holes* that serve as 'backbones' of the network that link the unconnected concepts together (Burt, 2004; Nielsen and Thomsen, 2011). Without these themes, the research area or field would be fragmented. Therefore, to assess this information, it is necessary to compute the network's core–periphery structure (Rombach et al., 2014). To

Table 2
Research Themes of 2011–2020: size, total frequency (TF), co-word frequency (CW-F), centrality (Centr.), density.

ID	Keywords (2011–2020)	Size	TF	CW-F	Centr.	Dens.
C1	Older adults, gestures, mobile, touch, motor impairments, input, target acquisition, input devices, empirical study	9	345	932	1.00	4.5
C2	Blind and visually impaired (BVI), navigation, wayfinding	3	346	792	0.96	22
C3	Haptics, multimodal interaction, quantitative research, visualisation, explicit interaction, crowdsourcing, tactile, image processing, nonvisual, computer vision	10	235	616	0.86	1.73
C4	Deaf or hard of hearing (DHH), sign language, captions, feedback	4	131	288	0.66	7.00
C5	Design, inclusive, co-design, youth, therapy, games, autism, learning, qualitative research, digitisation, education, collaborative, information assembly, methodology, sensory, abilities	16	469	1072	1.00	1.63
C6	Auditory, web, text entry and manipulation, reading, eye interaction	5	312	722	0.97	6.80
C7	Programming, prototyping, fabrication	3	79	192	0.68	4.67
C8	Adaptive interface, affective computing, communication technology, security, explicit interaction, personalisation, wheelchairs, spatial, augmentative and alternative communication (AAC), modelling, sensing, wearables, displays, privacy, augmented, social media, robots	25	577	1372	1.0	0.72

Table 3
Summary of popular, core, and backbone topics for Decade 1 (2001–2010): #, popular topic, its frequency (Freq.), core topic, its coreness (Core), backbone topic, and its constraint value (Constr.).

#	Popular topic	Freq.	Core topic	Core	Backbone topic	Constr.
1	**Blind and visually impaired (bvi)**	119	**Blind and visually impaired (bvi)**	0.986	Artificial intelligence	0.091
2	**Auditory**	97	**Auditory**	0.972	**Auditory**	0.100
3	**Web**	69	**Mobile**	0.958	**Blind and visually impaired (BVI)**	0.102
4	**Mobile**	48	**Design**	0.944	**Design**	0.112
5	**Design**	41	Qualitative research	0.931	**Mobile**	0.114
6	**Older adults**	41	**Older adults**	0.917	**Older adults**	0.114
7	**Programming**	38	**Web**	0.903	**Cognitive impairments**	0.122
8	**Cognitive impairments**	34	**Cognitive impairments**	0.889	**Web**	0.123
9	**Evaluation**	34	Visualisation	0.875	**Programming**	0.126
10	**Usability**	34	**Text entry and manipulation**	0.861	Motor impairments	0.130

* In bold appear the most popular topics that are present in all categories.

demonstrate how the keywords in Tables 1 and 2 are linked to each other, we created a network map for the keywords for both decades. The resulting network maps for the keywords are shown in Fig. 4. We assess the core–periphery structure of the network using the following criteria:

- Popularity – how frequently a keyword is used.
- Coreness – how connected a keyword is to other topics, measured on a scale [0–1]. Higher values indicate better connectedness to other keywords and thus a greater importance for the network (Rombach et al., 2014).
- Constraints (structural holes, *i.e.*, backbones of the field) – how connected a research keyword is to other distinct topics, measured on a scale [0–1]. Constraint values are an inverse measure of structural holes; hence, lower values indicate better connectedness (Everett and Borgatti, 2020).

Our results are summarised in Tables 3 and 4 for Decade 1 and 2 respectively. We find that the most popular keyword in both decades is 'blind and visually impaired (BVI)'. In both decades, other popular keywords are: 'mobile', 'design', 'older adults'. Although these keywords are common for both decades, we can still observe a change in research interest with diverging keywords such as 'cognitive impairments', 'programming', 'visualisation', and 'haptics' in Decade 1, and 'touch', 'games', 'text entry and manipulation', and 'web' in Decade 2.

Regarding the coreness of the keywords, we observe that the most connected topics for Decade 1 and Decade 2 were 'blind and visually impaired (BVI)', 'auditory', 'mobile', 'design', 'text entry and manipulation', and 'web'. Nevertheless, there is a difference in the top ten core topics list in Decade 1 and Decade 2. For example, in Decade 1 the remaining core topics included 'qualitative research', 'older adults', 'visualisation', and 'cognitive impairments'. Whereas in Decade 2 these keywords were replaced with 'touch', 'eye interaction', 'gestures', and 'reading'.

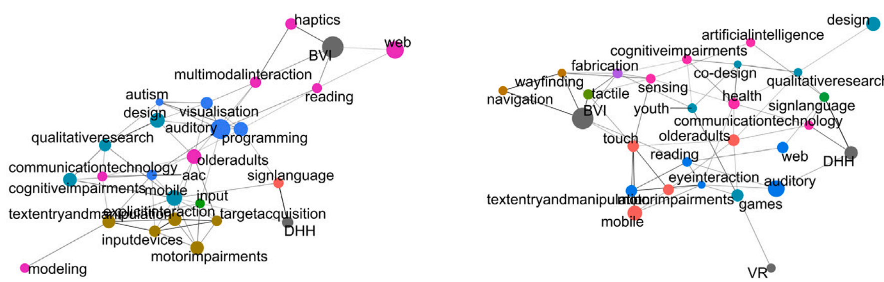
Further, similar trends can be detected from observing structural holes in the keyword networks. For example, we observed that some structural holes for Decade 1 and Decade 2 are the same, whereas others have changed. The structural holes that remained unchanged for both decades are: 'blind and visually impaired (BVI)', 'design', 'older adults', and 'cognitive impairments'. In Decade 1, other structural holes included 'artificial intelligence', 'auditory', 'mobile', 'web', 'programming', and 'motor impairments'. In Decade 2, this list has been replaced with 'autism', 'cognitive impairments', 'health', 'modelling', 'in-the-wild', 'displays', and 'affective computing', clearly indicating a shift in research interests in the second decade as compared to the first decade.

To reduce visual clutter, Fig. 4 illustrates 25 nodes of the network map, and 26 nodes of the network map for Decades 1 and 2, respectively. More detailed network keyword maps are available in the supplementary materials.

Table 4
Summary of popular, core, and backbone topics for Decade 2 (2011–2020): #, popular topic, its frequency (Freq.), core topic, its coreness (Core), backbone topic, and its constraint value (Constr.).

#	Popular topic	Freq.	Core topic	Core	Backbone topic	Constr.
1	**Blind and visually impaired (bvi)**	341	**Blind and visually impaired (bvi)**	0.98	**Blind and visually impaired (bvi)**	0.075
2	**Auditory**	170	**Auditory**	0.967	**Older adults**	0.094
3	**Mobile**	118	**Text entry and manipulation**	0.950	Autism	0.096
4	**Design**	117	**Mobile**	0.933	Cognitive impairments	0.096
5	**Deaf or hard of hearing (dhh)**	90	**Touch**	0.917	**Design**	0.097
6	**Games**	71	**Design**	0.900	**Health**	0.099
7	**Older adults**	65	Reading	0.883	Modelling	0.101
8	**Text entry and manipulation**	62	Web	0.867	In-the-wild	0.103
9	**Touch**	62	Eye interaction	0.850	Displays	0.104
10	**Health**	62	Gestures	0.833	Affective computing	0.107

* In bold appear the most popular topics that are present in all categories.



(a) Network map for 2001–2010 (b) Network map for 2011–2020

Fig. 4. Overview of keyword networks in the accessibility research field. The size of the nodes is proportional to the frequency of the keywords, the colour of the node maps to the corresponding cluster, and the thickness of the links is proportional to the co-occurrence correlation for that distinct pair of keywords.

4.3. Correspondence analysis

Finally, to better understand which topics drew the interest of the research community throughout the years 2001–2020, we plotted Correspondence Analysis (CA) (Gifi, 1990) factor maps of the 80 most frequent keywords (40 keywords from Decade 1 and from Decade 2), presented in Figs. 5 and 6. We retained only the 40 most popular keywords in order not to overcrowd the CA network maps. CA is used to analyse and explain the relative relationship between the group of variables based on a contingency table (Gifi, 1990). In our example, CA allows us to examine and visualise the relationship between the keywords and years when the new topics emerged. To be precise, CA uses chi-squared statistics to analyse frequencies formed by categorical data and provides factor scores for row and column variables of the contingency table. These factor scores are then used as coordinates to visualise the association between variables (*i.e.*, keywords and years) in a two-dimensional space on a common set of orthogonal axes. Hence, to visualise which topics drew the interest of the research community throughout the years 2001–2020, we plotted CA factor maps of the 80 most frequent keywords (40 keywords from Decade 1 and from Decade 2), presented in Figs. 5 and 6. We retained only the 40 most popular keywords in order not to overcrowd the CA network maps. The CA factor maps show a clear shift in research interests within accessibility research and how different years have contributed to the emergence of different keywords.

In Fig. 5, we can observe that the years 2004–2007 are located on the left-hand side of the graph, with keywords such as 'text entry and manipulation', 'target acquisition', 'web', 'blind and visually-impaired', 'navigation' and many others describing the popular topics for these years. The years 2008–2010 are located on the right-hand side of the CA factor map, surrounded by topics such as 'adaptive interfaces', 'tactile', 'mobile', 'sensing', 'haptics', and many others. This positioning of years indicates that there was a shift in research keywords within this decade. Furthermore, the years 2001–2003 are not visible on the graph. This is because the frequency of keywords published in the papers during 2001–2003 was significantly lower than the frequency of keywords in published articles during 2004–2010. This indicates that accessibility research was relatively sparse at the beginning of Decade 1. Hence, the keywords for these years were not shown in the CA factor map presented in Fig. 5. We can further observe that some years and keywords are located close to each other. For example, the years 2004 and 2005, 2006 and 2007, and 2008–2010 are placed relatively closer to each other on the CA factor map. This is an indication that these years can be regarded as a *cluster*, meaning the keywords published in these years were strongly and closely linked to each other.

For Decade 2, we can also observe a clear shift in research topics (see Fig. 6. The earlier years of Decade 2 are located on the right side of the diagram, whereas the latter years are located on the left side of the diagram. The years 2011–2013 form a cluster; and, hence, indicate that their keywords have stronger links to each other – *e.g.*, 'haptics' and 'touch'. Starting from 2014, we can observe a shift in research topics as displayed by the years 2014–2020 with 2014–2016 being located along the central vertical axis, and the rest of years being located on the left side of the CA factor map. Moreover, the years 2014–2015, and 2018–2020 are placed closer to each other, forming a cluster around keywords such as 'health' and 'affective computing'. Similarly, 2016 and 2019 are also located closer to each other, creating another cluster around the terms 'modelling', 'navigation', and 'co-design'.

To summarise, the research focus in accessibility research has shifted throughout the years, with the later years of each decade

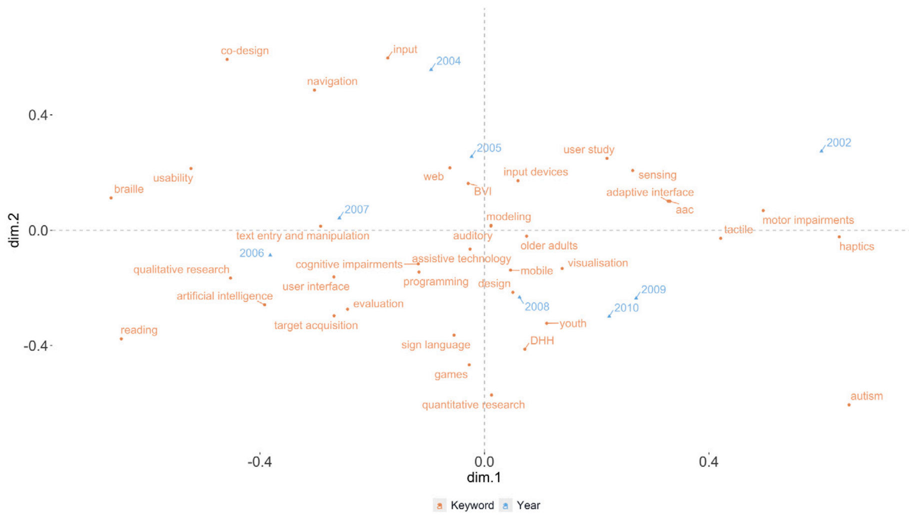


Fig. 5. Correspondence analysis for Decade 1 (2001–2010).

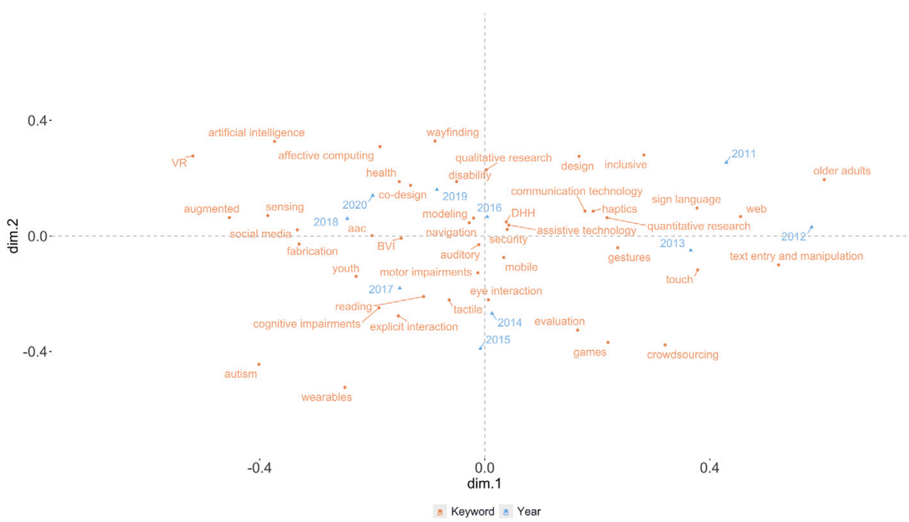


Fig. 6. Correspondence analysis for Decade 2 (2011–2020).

occupying the left side of the diagram. In contrast, the earlier years are located on the right side of the diagram for both decades, clearly demonstrating a shift in research topics.

5. Discussion

5.1. Shift in research themes

Our results show that in Decade 1, the motor themes of accessibility research were ‘motor impairments’, ‘input devices’, ‘cursor’, ‘explicit interaction’, ‘submovements’, ‘gestures’, ‘text entry and manipulation’, ‘touch’, ‘target acquisition’, and ‘Fitts’ law’ from cluster C2 (Table 1, Fig. 3). These keywords are closely related, and it is therefore not surprising to see them grouped in one cluster. The dominance of these topics also remained stable and strong in the second decade (Table 2, Fig. 3). However, our findings indicate that the research community’s interest in these research themes declined in Decade 2 as the cluster shifted to Quadrant 4. The cluster size remains almost unchanged, with some keywords being removed and others added to it. For example, in Decade 2, ‘older adults’, ‘mobile’, and ‘empirical study’ are the new keywords added to the cluster, while ‘cursor’, ‘explicit interaction’, ‘Fitts’ law’, ‘text entry and manipulation’, and ‘submovements’ were removed. This can be explained by the general availability of mobile devices and subsequent growth of research attention towards them, for example to be used as a sensing instrument for research purposes (Liu et al., 2014a). Interestingly, the ‘older adults’ keyword remained in Quadrant IV throughout both decades. This indicates that this keyword has the potential to become a significant topic within accessibility research in the future. A possible explanation as to why the ‘older adults’ keyword was added in the cluster C1 in the second decade, as well as outlining its future potential importance, is the increased attention towards the global ageing population and the fact that this keyword often co-occurs with different disabilities, including motor impairments, cognitive, or memory impairments (Mack et al., 2021). This indicates that when conducting research, accessibility researchers recruit older adults when investigating these impairments. Our findings support the argument by Mack et al. (2021) as we also show that ‘older adults’ appears in the same cluster together with such keywords as ‘blind and visually-impaired’, ‘memory aid’ linked to visual impairments and memory impairments in Decade 1 (Table 1), and with motor impairments in Decade 2 (Table 2).

Two new research themes became motor topics in accessibility research in the second decade. These topics originate from clusters C2 and C6 (Fig. 3, Table 2). The new motor themes for Decade 2 cluster C2 are ‘blind and visually impaired’, ‘navigation’, and ‘wayfinding’, and from cluster C6 are: ‘auditory’, ‘web’, ‘text entry and manipulation’, 'reading', and 'eye interaction'. These keywords are also closely linked to each other and can be seen in works directed at addressing the needs of the blind and visually impaired (Mack et al., 2021; Pandey et al., 2020; Liu et al., 2021; Kuber et al., 2007). Our findings show that the topic of 'blind and visually impaired' has evolved from being a general and broad topic with a rather underdeveloped prior body of works (Quadrant IV of the strategic graph in Fig. 3) in Decade 1, into a motor theme of accessibility research in Decade 2. Our results are in line with the literature, showing that blind and visually impaired communities have attracted greater attention from the HCI community in the past decade (Mack et al., 2021; Abbott et al., 2019). Mack et al. (2021) speculate that this increase in attention might be due to different factors, including funding mechanisms, the concreteness of visual accessibility problems of different HCI technologies, and the focus on the blind and visually impaired community in the public disability discourse. Our analysis confirms this differentiation in the accessibility landscape, with 'blind and visually impaired' emerging as a motor theme whereas *e.g.*, 'deaf or hard of hearing' remains respectively in Quadrant II (developed but isolated) throughout both decades.

In the second decade, such keywords as 'affective computing' and 'wearables' are located in Quadrant IV. It is important to note that these keywords were located in Quadrant III in Decade 1, indicating that they were either emerging or disappearing themes. Hence, their move to Quadrant IV in the second decade demonstrates that these themes have gained importance in the research community over the past decade and have received increased interest from researchers; although the cluster itself still stays quite broad. Furthermore, in the second decade, such topics as 'prototyping' and 'fabrication' are located in Quadrant II indicating that these research themes are either emerging or declining. Given that these research keywords are not located in any of the clusters in Decade 1, we can conclude that these topics are emerging. It is not surprising as prototyping has become more popular within the community with increased availability of 3D printing technology (Ludwig et al., 2014). 3D printing technology became widely available in the second decade of the 21st century and empowered accessibility communities to create Do-It-Yourself (DIY) assistive technologies (Hurst and Tobias, 2011). Accessibility communities have been widely successful in designing DIY artefacts with a wide variety of prototypes, including upper limb prosthetics (Hofmann et al., 2016), customised thumb splints (Hofmann et al., 2019), wheelchair transfer boards (Hofmann et al., 2019), and tactile 3D printed objects to support special education for visually impaired (Buehler et al., 2014).

5.1.1. Research themes remaining static through the decades

The keywords 'deaf or hard of hearing' (DHH) and 'sign language' remained in Quadrant II during both decades. This indicates that these research themes remain developed, but isolated. These themes are internally well-structured with a consistent amount of attention. However, these research themes neither gained nor lost interest from the research community, and have remained well-structured niche topics within accessibility research over the past two decades. Our findings corroborate prior works, showing that the DHH research community is the third most popular community in accessibility research after the BVI and motor impairment communities (Mack et al., 2021). Given that approximately 360 million people in the world live with a hearing impairment (WHO, 2018), we predict that the DHH research will continue to be a mainstay of accessibility research, particularly due to the expected growth of research in smart home and smart environments that is not accessible for people with hearing impairments (*e.g.*, relies on speech or sound interaction) (Jain et al., 2019).

Another interesting research theme in accessibility research is 'artificial intelligence'. It was located in Quadrant III in Decade 1; however, it was not represented in any of the clusters in Decade 2. This indicates that within the 20 years artificial intelligence did not become a motor theme within accessibility research. However, the topic of adaptive interfaces remains stable within the Quadrant IV of the strategic diagrams in both decades. Hence, we argue that given the overall trend of HCI research and a growing interest in artificial intelligence and adaptive interfaces (Bughin et al., 2017), these topics have a potential to become a trending motor research theme in the near future. Furthermore, accessible design solutions increasingly rely on artificial intelligence. For example, assistive writing tools use statistical language model systems or neural machine translation models to improve writing for people who cannot access standard keyboard input (Wu et al., 2019). Furthermore, blind or visually impaired users were one of the early adopters of AI in computer vision-based applications (Bigham and Carrington, 2018). Similarly, deaf or hard of hearing people can benefit from AI systems that provide automatic image captions on social media platforms (Wu et al., 2017) or shopping websites (Stangl et al., 2018).

Quadrant IV in the diagrams of both decades (Fig. 3) contains clusters with keywords that are weakly linked to each other; hence, explaining the size of the clusters, *i.e.*, large cluster sizes containing weakly linked keywords. Nevertheless, themes in this quadrant can gain considerable significance in the research field, even though they are weakly structured. Fig. 3 and Tables 1 and 2 show that some keywords in clusters located in Quadrant IV (Decade 1) moved to other quadrants of the strategic graph in Decade 2. With a few new keywords being introduced to the clusters, the majority of keywords remain within the same quadrant (*e.g.*, 'communication technology', 'inclusive', 'education', 'learning', 'therapy', 'information assembly', 'personalisation', 'augmentative and alternative communication (AAC)', 'modelling', and 'sensing'). This potentially indicates that 20 years were insufficient for these topics to build an extensive body of work, and these topics still remain weakly structured.

5.2. Accessibility research roadmap

According to our analysis, the themes presented in C6, C7, and C9 in the strategic diagram for Decade 2 (Fig. 3(b)) show great potential for gaining considerable significance within accessibility research. It is understandable why the majority of the keywords in these clusters can become important topics. For example, due to the crucial role that communication plays in our daily life, it is essential to enhance the accessibility of communication technology to make it available for disabled people (Alonzo et al., 2020; Tigwell et al., 2020). On a different note, 'adaptive interfaces', 'wearables', 'augmentative and alternative communication', and 'sensing' often allow for alternative ways to interact with the environment or learn about the environment due to constraints presented by permanent (Gajos et al., 2007; Mott and Wobbrock, 2019) or situational impairments (Sarsenbayeva et al., 2016, 2018; Wobbrock, 2019).

Another noteworthy topic is 'affective computing', which has recently gained significant interest in HCI research (Zhang et al., 2018; Yang et al., 2022; Tag et al., 2022b). Regardless of human abilities, people face emotional problems. For example, due to impaired vision, blind or visually impaired people face challenges in understanding the emotions of other people and being empathetic, as well as showing their own emotions (Lang et al., 2017). This happens because people tend to show their emotions using visual cues, *e.g.*, body language, eye gaze, and facial expressions (McDaniel et al., 2018). Hence, blind or visually impaired people cannot (fully) access this information exchange in social settings. This potentially leads to social avoidance, isolation, and psychological problems, including depression and social anxiety (McDaniel et al., 2018). These problems are even more exacerbated when communication happens online. Due to the loss of crucial information cues caused by compressed voice and video signals as a compromise to stable live streaming, micro-facial expressions and details in the tone of voice may get lost. Furthermore, visual information of body postures is often lost due to the limited field of view of the camera (Khamis et al., 2018; Tag et al., 2022a; Sarsenbayeva et al., 2020). However, prior works have shown that the accessibility of biosignal data, *e.g.*, heartbeat information, potentially increases empathy levels of users who are deaf or hard of hearing, thus offering solutions to this problem (Winters et al., 2021).

Moreover, research on accessibility can complement research on affective computing, and vice versa, as they both have converging goals that can lead to mutually beneficial outcomes. For example, people diagnosed with neurodevelopmental disorders (*e.g.*, autism) may have difficulties in socially engaging with others as well as recognising and reading their emotions (El Kaliouby et al., 2006). Accessibility research can develop tools and interfaces to assist people with neurodevelopmental disorders in social interactions by providing emotional context to promote socioemotional skills. At the same time, one of the main goals of affective computing is to equip robots and computational agents with socioemotional skills (El Kaliouby et al., 2006), an overlapping goal with accessibility research. Furthermore, it is important to focus on the accessibility of affective computing technology, *e.g.*, emotion detection systems. The need for mental health support will increase – expressed in the projections of this market to double in size by 2026 – due to the uncertainty during the COVID-19 pandemic and restrictions to our regular lifestyles that have caused interruptions to existing mental health services in many countries (Tag et al., 2022c; Markets and Markets Research Private Ltd., 2021; Yamada et al., 2021). Moreover, it opens further opportunities for accessibility research to develop solutions that can assist with challenges pertaining to mental health and well-being, an emerging trend in accessibility research (Mack et al., 2021).

Similar to 'affective computing', another important topic that can gain significant influence in the community is 'cognitive impairments'. Mack et al. (2021) show that currently, only 9.1% of their reviewed publications accounted for the topic of 'cognitive impairments'. The current state of 'cognitive impairments' research topic can be explained by the fact that HCI technology has not yet reached the level to support users with cognitive impairments. For example, there are specific technological solutions to address the needs of different impairments, *e.g.*, screen readers for blind or visually impaired, video captions for deaf or hard of hearing. However, there is currently a great lack of technology to address the needs of the cognitively impaired (Kulkarni, 2019). Our analysis shows that this topic is located in Quadrant IV, indicating that the topic is underdeveloped yet transversal and, with time, will potentially become an increasingly investigated topic in accessibility research.

Furthermore, it is important to note that keywords like 'design', 'inclusive', 'co-design', 'smart environments', and 'in-the-wild' form another theme within Quadrant IV are likely to increase in influence within accessibility research. This is not surprising given the current state-of-the-art of accessibility research. It has been shown multiple times in the literature that, first of all, there is a great challenge in hiring developers with accessibility knowledge and experience when developing accessible technologies (Lawrence and Bellard, 2017). This leads to a lack of understanding of techniques that people with disabilities use when interacting with technology (Crabb et al., 2019).

In addition, prior research has shown that user representation in accessibility research is often problematic due to the difficulties of recruiting participants from disabled user groups (Sears and Hanson, 2011). By increasing the representation of impaired users, it becomes easier to define new research directions and community needs (Spiel et al., 2020), while also opening up the possibility of involving these users in the design and co-design of prototypes. This is particularly important given that prior work has demonstrated that non-disabled participants and disabled participants behave differently during the studies and approach problem solving with different strategies (Sears et al., 2001; Walker and Mauney, 2010). Lastly, it is crucial to move studies from the controlled laboratory settings to more naturalistic environments as this can potentially uncover issues of novel access technologies faster (Branham and Kane, 2015). Branham and Kane (2015) further argue that longitudinal deployments in different in-the-wild settings (*e.g.*, 'home', 'public', 'schools', and 'workplaces') may better capture the varying accessibility of the technology and efficiently reveal its suitability in different environments.

Finally, accessibility researchers argue that it is necessary to contribute towards best practices in teaching accessibility, as it can potentially increase the capacity and expertise in industry (Mack et al., 2021; Crabb et al., 2019). Perhaps, for this reason, we observe a cluster of keywords related to teaching practices (*e.g.*, 'youth', 'learning', 'education', 'information assembly') in Quadrant IV of the strategic diagram for Decade 2, presented in Fig. 3(b). For example, Putnam et al. (2012) argue that a better understanding of how academic professionals consider and receive accessibility has a significant influence on educational programmes in HCI and UX. It can also contribute to the preparation of future designers and researchers working on accessibility (Putnam et al., 2012; Sarsenbayeva et al., 2022). In other words, teaching and studying accessibility can support identifying the most impactful problems in accessibility, enhance and foster critical thinking about the research, and create new possibilities and opportunities for interdisciplinary collaboration (Mankoff et al., 2010; van Berkel et al., 2023). Therefore, it is essential to include accessibility in university curricula to build a robust future community of accessibility scholars and designers.

5.3. Limitations

By analysing ASSETS, TACCESS, IJHCS, and CHI, we describe the development and progression of accessibility research within HCI. Our sample excluded papers published in non-HCI venues (*e.g.*, publications in medical journals, International Conference on Computers Helping People with Special Needs), and hence the accessibility advances made in other fields like biomedical engineering or contributions outside of this representation of the HCI community are not captured here. This decision was intentional, as we specifically wanted to examine the development of accessibility from the perspective of user-centred design to distil lessons for the HCI community. Furthermore, our analysis does not allow for viewing the details of the research trend change relative to each other, *i.e.*, if a specific topic has plateaued, declined, or grown within a particular period of the decade. For analysing such detailed trend changes, it is necessary to follow a different methodological approach, such as a systematic literature review with a targeted focus on each research trend. Finally, given that we based our analysis on keywords, we assume that the keywords accurately reflect the paper content. We believe keywords to be the most insightful approach to paper categorisation, with alternatives such as the ACM's Computing Classification System (CCS) being highly granular and used inconsistently by authors. Nevertheless, our keyword-driven analysis might result in a bias from authors in their keyword selection practices. We aimed to minimise this possibility by manually revising the keywords and grouping them under unified overarching keywords.

6. Conclusion

In this work, we analyse the intellectual progress of accessibility research in HCI over the past two decades. We employed co-word analysis to assess and examine the conceptual structure and intellectual evolution of accessibility research published at four leading Accessibility venues – ASSETS, TACCESS, IJHCS, and CHI. Our findings demonstrate a shift in research topics between 2001 and 2020 with significant growth of accessibility research within HCI in the past decade. Our results show that there are currently several motor themes in accessibility research which are summarised in two clusters. To mention a few, these motor themes include topics such as 'blind and visually impaired', 'navigation', 'wayfinding', 'design'. Furthermore, the results of the core–periphery analysis of the keyword network for both decades also demonstrates a shift in research interests within the

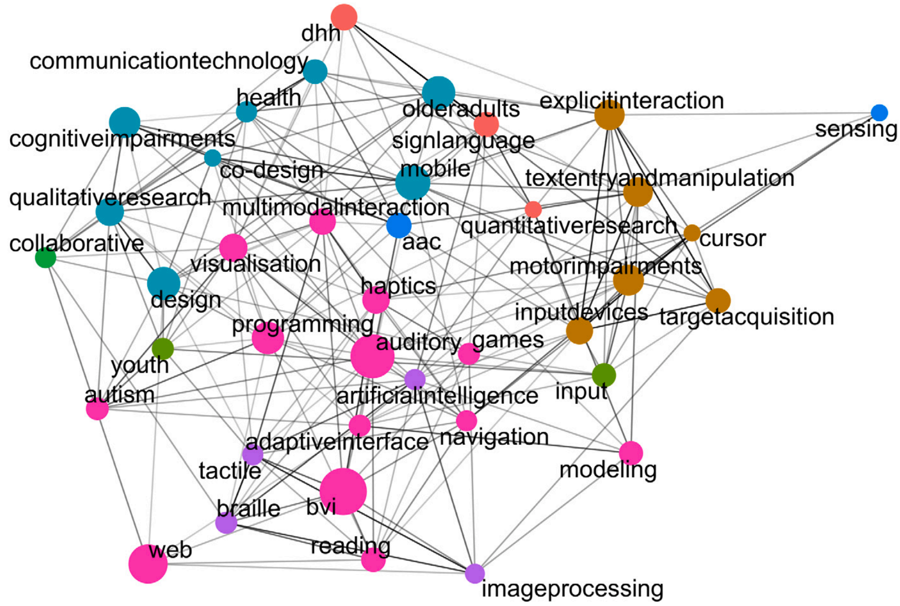


Fig. 7. Full network of keywords for Decade 1 (2011–2020).

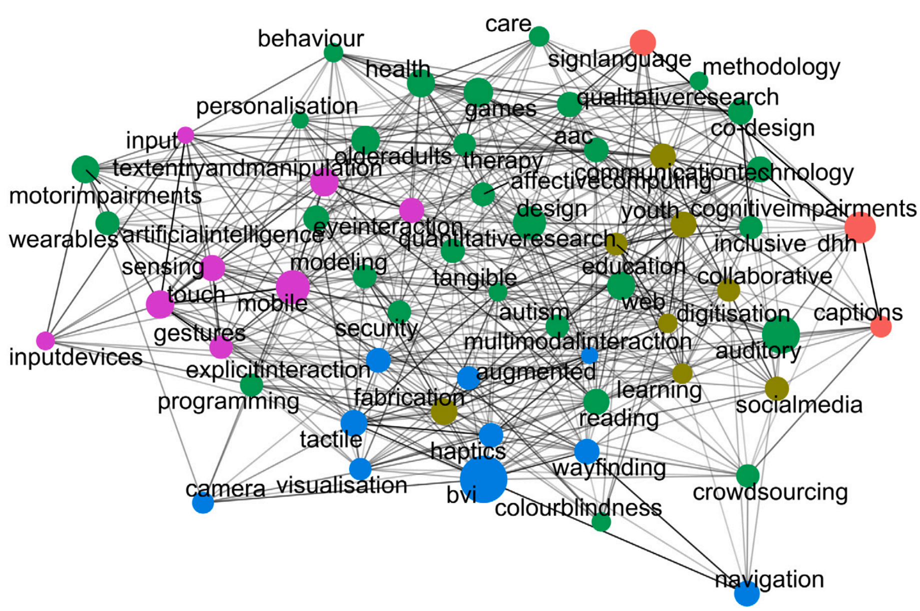


Fig. 8. Full network of keywords for Decade 2 (2011–2020).

community in the past two decades. For example, we demonstrate that the number of motor themes remained unchanged in both decades; however, the shift in the research community's interest was substantial. New motor themes of the recent decade include such topics as 'learning', 'education', 'qualitative research', and 'therapy' among others. We provide a roadmap for accessibility research and we speculate, as based on observed trends, that topics such as 'affective computing', the design and co-design of technology, empirical studies, and the teaching of accessibility practices will gain considerable traction in the coming years. Our findings can help guide both early career researchers and experienced academics, as they highlight opportunities and directions for conducting accessibility research.

CRediT authorship contribution statement

Zhanna Sarsenbayeva: Conceptualization, Methodology, Data curation, Writing – original draft. **Niels van Berkel:** Data curation, Methodology, Writing – review & editing. **Danula Hettiachchi:** Methodology, Writing – review & editing. **Benjamin Tag:** Data curation, Writing – review & editing. **Eduardo Velloso:** Writing – review & editing. **Jorge Goncalves:** Writing – review & editing. **Vassilis Kostakos:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

See Figs. 7 and 8.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhcs.2023.103018.

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