CHI 1994-2013: Mapping Two Decades of Intellectual Progress through Co-word Analysis

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ABSTRACT
This study employs hierarchical cluster analysis, strategic diagrams and network analysis to map and visualize the intellectual landscape of the CHI conference on Human Computer Interaction through the use of co-word analysis. The study quantifies and describes the thematic evolution of the field based on a total of 3152 CHI articles and their associated 16035 keywords published between 1994 and 2013. The analysis is conducted for two time periods (1994-2003, 2004-2013) and a comparison between them highlights the underlying trends in our community. More significantly, this study identifies the evolution of major themes in the discipline, and highlights individual topics as popular, core, or backbone research topics within HCI.

Author Keywords
Co-word analysis; bibliometric study; conceptual evolution; HCI; cohesion; coherence

ACM Classification Keywords
K2. History Of: Theory.

INTRODUCTION
The CHI conference has a long and rich history. In the last 20 years alone its 3152 publications have shaped and defined the field of human-computer interaction, making CHI a flagship HCI venue characterized by its strong multidisciplinarity. In this paper, we are interested in mapping how the landscape of the HCI field has evolved, as reflected in the record of CHI publications.

Harrison et al. [16] characterized the field of HCI into three intertwined and non-exclusive paradigms: human-factors; classical cognitivism/information processing based; and phenomenologically-situated. This simplified categorization makes it challenging to understand the field's evolution as a whole. As the authors note, it is difficult to assess "marginal" contributions that are hard to precisely place. HCI is indisputably a multidisciplinary field requiring a more in-depth analysis to reveal the intricacies of its evolution.

To contribute towards understanding the big picture of HCI evolution, we analyzed CHI's publications keywords since 1994, and for our convenience, we divided them into two 10-year periods: 1994-2003 and 2004-2013. Between 1994-2003, CHI was predominantly focused on fixed (or non-mobile) HCI. Since 2004, however, the field has grown at a high pace, due to the introduction of extended abstracts and electronic proceedings. The popularity of mobile phones, ambient media and social technologies has shifted HCI research towards mobile and social interaction, while new issues involving humans, such as crowdsourcing and privacy have taken the spotlight. We attempt to study and analyze HCI research foci transitions and reflect on their drivers and present status.

Our analysis relies on techniques from hierarchical cluster and graph theory, through the use of co-word analysis artifacts such as strategic diagrams and graphs. Co-word analysis is part of the co-occurrence analysis methods. It is a widely-applied bibliometric approach to describe the interactions among concepts, ideas, and problems and to explore the concept network within a scientific area [7,8]. A recently published paper of a *co-citation* analysis of the CHI proceedings [2] focused on authorship aspects of the proceedings and citation metrics for papers. Here we focus on the concepts that reflect our community and their evolution over time.

Co-word analysis rests on the assumption that a paper's keywords constitute an adequate description of its content as well as the links the paper established between problems: two keywords co-occurring within the same paper are an indication of a link between the topics to which they refer to [9]. The presence of many co-occurrences around the same word or pair of words points to a locus of strategic alliance within articles that may embody a research theme [9,30].

More importantly, by measuring the association strength of terms produced in a specific scientific discipline, co-word analysis allows researchers to identify key patterns and trends within the area [13,18,20]. It is assumed that a specific keyword with adequate frequency refers to a particular research topic while a cluster or pattern of keywords refers to a specific research direction or research theme. A change of research theme (*i.e.*, declining or emerging research interest) as well as the change of research topics within a research theme implies a paradigm change.

RELATED WORK
The main concepts we use in our analysis are *keywords*, *networks*, and *clusters*. *Keywords* appear on research papers, and two keywords appearing on the same paper are linked to form a *network* (or graph) of keywords. Analysis of this network helps us identify *clusters* (a set of closely-related keywords).

Our co-word analysis reduces a large space of descriptors (*i.e.*, keywords) into a network graph (*i.e.*, multiple related smaller spaces). Easier to comprehend but still retaining

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crucial information, this approach visualizes the interrelated concepts [11] and intellectual structure of a discipline into a map of the conceptual space of this field, and a time-series of such maps produces a trace of the changes in this conceptual space [13]. Co-word analysis has been widely utilized in mapping the conceptual networks of a diversity of disciplines, like business intelligence [29], consumer behavior [22], software engineering [11], patent analyses [10], biology [1,9], education [25], and library and information science [13,20,30]. As such, it makes sense to apply this technique to enrich our understanding of CHI.

Given a network of keywords, we can use network analysis and strategic diagrams to characterize the field. Keywords and clusters have different properties, depending on how they are linked with each other. For instance, bridges between two nodes (*i.e.*, linked nodes) in a network perform a valuable function in allowing communication and facilitating the flow between otherwise isolated regions of the network, also known as *structural holes* [24]. The greater the number of bridges associated with a research topic or theme, the more it serves to connect otherwise isolated research topics or themes. Keywords with a great number of structural holes serve as the *backbone* of the whole network. If these are removed from the network, the whole network will collapse into a number of separated and unconnected research sub-fields, therefore losing its scientific cohesion and identity.

When computing a network's *core-periphery* structure, it becomes possible to determine which nodes are part of a densely connected core (*i.e.*, with a higher number of bridges) and which are part of a sparsely connected periphery [5,26]. Core nodes are typically well connected to peripheral nodes. Peripheral nodes are sparingly connected to a core or to each other. In a keyword network it is expected that, as the body of knowledge grows, peripheral nodes become core nodes, thus allowing for the emergence of new peripheral nodes. Research topics with a high core value delimit the main body of HCI knowledge, and represent important knowledge-growing points of the main body of the field.

In our work we rely on two graph theory concepts to map the field of HCI: *density* and *centrality*, defined as follows:

- *Density*, or internal cohesion, measures the *strength of the links that tie together the cluster of keywords* making up the research theme. This can be understood as a measure of the theme's development [17,22]. Density offers a good representation of the cluster's capacity to maintain itself and to develop over the course of the time in the field [7,17]. The *higher* the density, the more *coherent* the cluster is and the more likely it is to contain inseparable expressions;
- *Centrality* measures the *degree of interaction of a theme with other parts* of the network [24]. In other words, it measures the strength of external ties of a research theme to other research themes, and can be referred to as a measure of the importance of a theme in the development of the entire research field [22]. The greater the number and the strength of a theme's connections with other themes, the more central this theme will be to the whole network [3].

By combining both concepts we then created *a strategic diagram*. Strategic diagrams are two-dimensional plots that have been widely used in prior co-word analysis studies [7,11,20,22]. The *x-axis* shows the *strength of interaction between a specific research theme with others* (*i.e.*, centrality). The *y-axis* reflects the density of the research theme, or the *internal cohesion of a specific research theme* (see **Figure 1**).

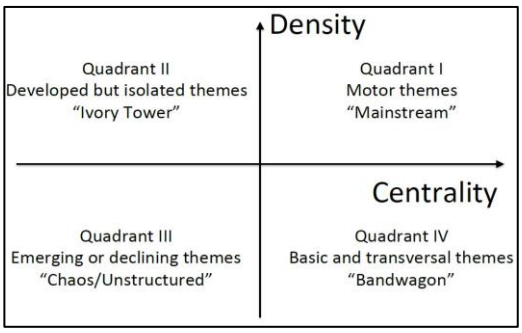


Figure 1. Strategic diagram's degree of density and centrality.

The location of a given research theme within this strategic diagram characterizes the theme in the context of the whole discipline:

Quadrant I (**Figure 1**, top-right): both internally coherent and central to the research network in question. Known as the motor-themes of the discipline given that they present strong centrality and high density;

Quadrant II (**Figure 1**, top-left): coherent but low centrality themes. These themes are internally well structured and indicate that a constituted social group is active in them. However, they have rather unimportant external ties resulting in specialized work that is rather peripheral to the work being carried out in the global research network;

Quadrant III (**Figure 1**, bottom-left): weakly developed with marginal interest in the global research network. These themes have low density and low centrality, mainly representing either emerging or disappearing themes;

Quadrant IV (**Figure 1**, bottom-right): weakly structured themes. These are strongly linked to specific research interests throughout the network but are only weakly linked together. In other words, prior works in these themes is under-developed yet transversal, with potential to be of considerable significance to the entire research network.

DATA

The ACM digital library provided us data on the papers published at the CHI conference between 1994 and 2013. According to Bradford's law [6], a fundamental theory in bibliometric analysis, a small core of publications will account for a sizeable portion of the significant literature in terms of citations received (*i.e.*, as high as 90%), while attempts to gather 100 percent of it will add articles to the core at an exponential rate [14]. Considering the relevance of the CHI conference to the field of HCI, an analysis on the CHI articles should enable us to attain a fair overview of the field's development: a total of 3152 CHI articles (full papers and notes) were published between 1994 and 2013, containing 16035 keywords (mean of 5.09 per article) (see **Figure 2**). For a small number of papers we had to manually extract the keywords from the electronic version of the manuscript (PDF) using a script.

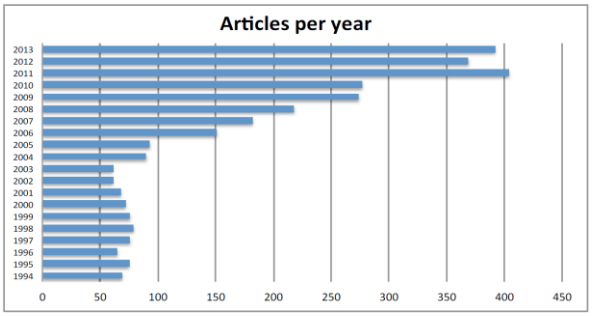


Figure 2. Number of publications per year at CHI.

The sample was split in two datasets of ten years each, to investigate the paradigm change in HCI over the past 20 years. The number of the papers published in 1994-2003 (N=702) is smaller than the number of the papers published in 2004-2013 (N=2450), suggesting that the research in HCI has grown considerably in the last ten years. We manually standardized the keywords through synonyms mergence (*e.g.*, "mobile devices" and "handheld devices" were merged; "ubicomp" and "ubiquitous computing" and so on) and *filtered broad* items (*e.g.*, "HCI" and "human computer interaction") [18,20,27,30]. The *synonyms mergence* considered the top 2029 keywords that appear at least twice in a dataset with regard to the merging of singular and plural forms of nouns, gerunds, nouns, abbreviations and acronyms.

The frequency of keywords follows a power-law distribution (see **Figure 3**) with an alpha of 3.46 (R^2=0.51), indicative that the research structure of HCI in the past 20 years is a *scale-free network*, a network where a small number of popular nodes (*i.e.*, keywords) act as hubs connecting other concepts. These hubs shape the overall network, which in this case reflects the intellectual structure of HCI represented by and through keywords. This scale-free characteristic suggests that a small number of popular keywords can capture major research directions and major influences in the field [20,30]. Therefore, in our analysis we retained only those keywords which appeared more than six times during 1994-2003, or more than 14 times during 2004-2013. Thus, 94 keywords were selected for the period of 1994-2003 (total frequency=1154), covering 556 (79.2%) of the 702 papers published during this period. Similarly, for the period of 2004-2013, 95 keywords were selected (total frequency=2692), covering 1602 of the 2450 papers published, *i.e.*, 65.3% of the publications. With fewer but popular keywords we could then reliably characterize the entire network of keywords.

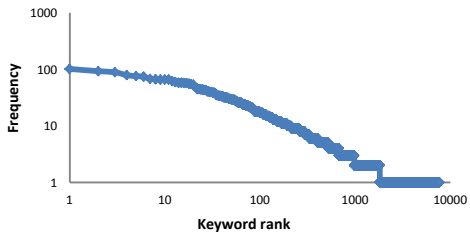


Figure 3. Power-law distribution of keyword frequency (in logarithmic scale). Power-law distributions resemble a straight line when on logarithmic scale.

RESULTS

Identifying the major research themes

First, we conducted hierarchical clustering using Ward's method with Squared Euclidean Distance as the distance measurement [28]. We adopted a supervised clustering method to reach as many clusters as possible while maintaining content validity and cluster fitness [18,20,30]. The 94 keywords for the 1994-2003 samples led to 14 clusters (labeled as A1-A14, in **Table 1**). Each cluster represents a research theme or subfield [20,30]. Similarly, the 95 keywords of 2004-2013 samples led to 14 clusters (labeled as B1-B14, in **Table 2**). The top-3 most frequent keywords are shown in bold, and are used to label each cluster [18,20,30]. In **Tables 1** and **2** we show for each theme:

- *Keywords*: the set of keywords that constitute this theme;
- *Size*: the number of keywords in the theme;
- *Frequency*: how often, on average, a keyword in this theme appears in our dataset;
- *Co-word frequency*: how often, on average, two keywords in this theme appear on the same paper;
- *Cohesion coefficient*: measures the extent to which when a keyword of this theme appears on a paper then another keyword of this theme also appears on a paper. Indicates the *similarity* or *dissimilarity* of keywords in a theme. Themes with *higher cohesion coefficient* are *more developed* or *bridging* research themes [20];
- *Centrality*: the degree of interaction of a theme with other parts of the network [24]. We calculate a localized version of this metric using the standard value 2 for the K-step reach. Thus, our centrality metric evaluates how the keyword connects all other keywords that can be reached through 2 connections;
- *Density*: measures the internal cohesion, or the strength, of the links that tie together the cluster of keywords making up the research theme [7,17]. To minimize the possible bias caused by the different sample sizes of the two periods, when calculating the overall network density, we rely on a binary version of the keyword co-occurrence matrix. This matrix only uses values 1 ("connected") or 0 ("not connected") to characterize every pair of keywords.

We constructed two strategic diagrams to visualize the cohesion and maturity of the research themes in HCI, using the centrality and density of each cluster as proposed by [7,11,18,20,22]. We plotted a strategic diagram for each period of analysis: 1994-2003 and 2004-2013 (**Figure 4a** and **Figure 4b**, respectively), based on Tables 1 and 2. The plots' origins are set to the average centrality and density across all the clusters for the designated sample, *i.e.*, (0.571, 2.305) for 1994-2003 and (0.635, 3.127) for 2004-2013. Comparing the intellectual structure of other fields (as shown in **Figure 5**), HCI lacks motor themes, and has lots of under-developed, but transversal research themes (see **Figure 4**).

We also calculated the overall network density for each network, to analyze whether the whole research field became more cohesive or not. The overall density of the HCI intellectual map has increased from 0.148 in 1994-

2003 to 0.206 in 2004-2013, meaning that the research field has become more cohesive over time.

Keyword network maps

For each of the two periods in our datasets we constructed a granular network of keywords using the following procedure. Each keyword is represented as a node in a graph, and we link together keywords that appear together on a paper. In **Figure 6 and 7** we show the result of this process for each of the two periods of analysis. We note that in these figures the size of a node is proportional to the frequency of the keyword, and the thickness of links is proportional to the co-occurrence correlation for that pair of keywords. Nodes of the same color belong to the same cluster, as presented next. To reduce visual clutter we only show a subset of the complete networks, omitting weaker ties and isolated nodes. A downside of this simplification is that, for example, "privacy" in Figure 6 appears to be disconnected from its own cluster. This is simply because weaker links are not included. Popular, core and backbone topics of HCI research

We next focused our analysis on individual keywords rather than underlying themes. A core-periphery analysis was conducted to determine the core research topics in the field from the perspective of the whole network structure. Twenty keywords (concentration=0.824) and 28 keywords (concentration=0.841) were identified to be the core research topics of the whole network in 1994-2003 and 2004-2013 respectively. Keywords or research topics were categorized as follows:

- *Popularity*: how frequently a research keyword is used;
- *Core*: [0-1] how connected is a research keyword with other topics;
- *Structural holes*: how connected is a research keyword with other otherwise distinct topics, thus supporting the topic structure (*i.e.*, the *backbone* of the field).

A higher core value indicates a topic that is well connected to other topics. A higher structural holes count suggests a keyword that brings together otherwise isolated topics. Topics with high scores on both of these metrics can be considered as the driving force for advancements in the field: without these topics, the field of HCI would be fragmented. We show these results in **Tables 3** and **4**.

ID	Keywords	Size	F	CW-F	Cohesion	Centr.	Density
A1	**computer supported cooperative work, interaction design, computer-mediated communication**, awareness, media spaces, audio, social interfaces	7	18.42	34.14	0.767	0.981	2.048
A2	**world wide web, empirical study, email**, Internet	4	15.25	27	0.662	0.532	2.500
A3	**ubiquitous computing, augmented reality, tangible user interface**, ethnography, mobile computing, PDA, learning, GOMS, education, mobile/handheld devices, groupware	11	13.90	21.90	0.437	0.888	0.909
A4	**visualization, user interface design, cognitive modeling**, evaluation, navigation, direct manipulation, agents, user modeling, animation, graphical user interfaces, design rationale, two-handed interaction, metaphor, prototypes, trust, haptic, mobile phone, pen computing, design, two-handed input, intelligent systems, speech recognition, intelligent interfaces	23	10.34	13.78	0.353	1.160	0.174
A5	**input devices, virtual reality, information visualization**, interaction techniques, 3D user interfaces, motor control, virtual environments, human performance	8	16.62	30.12	0.734	0.655	2.179
A6	**user interface, user studies, usability**, methodology, Empirical Evaluation	5	15	24.2	0.468	0.570	1.600
A7	**Fitts' law, information retrieval, hypertext**, browsing	4	18	33.25	0.624	0.465	4.000
A8	**children, educational applications, participatory design**, design techniques	4	13.25	25	0.795	0.287	3.833
A9	**multimedia, Interface design, collaboration**, video, mouse, gestures, field study, e-commerce, hypermedia, privacy, social computing	11	8.81	16.09	0.876	1.069	0.473
A10	**user-centered design, usability testing, usability engineering**, design process, videoconferencing	5	9.6	15.4	0.715	0.368	1.400
A11	**eye tracking, eye movements, multimodal interfaces**, gaze	4	8	14.25	0.855	0.376	2.000
A12	**annotation, digital libraries, documents**, dynamic query	4	7.5	10.5	0.617	0.276	1.167
A13	**programming by demonstration, end-user programming**	2	8.5	12	0.609	0.195	4.000
A14	**information foraging, information scent**	2	8	16.5	1.001	0.184	6.000

Table 1. Major research themes in HCI during 1994-2003 (size, frequency (F), co-word frequency (CW-F), cohesion, centrality (Centr.), density)

ID	Keywords	Size	F	CW-F	Cohesion	Centr.	Density
B1	***mobile phone*, sustainability, *ethnography***, online communities, HCI4D/ICTD, health, persuasive technology, motivation, *user-centered design*, behavior change, community	11	30.09	30.27	0.358	0.899	1.036
B2	***ubiquitous computing*, *privacy*, mobile**, *augmented reality*, wearable computing, *field study*, *mobile computing*, context-aware, *navigation*, *haptic*, large displays, human-robot interaction, music, computer vision, GPS, feedback, mobile interaction	17	26.94	28.58	0.416	1.064	0.654
B3	***visualization*, *collaboration*, *user interface***, wikis, *social computing*, tagging, *annotation*, personal information management	8	30.62	35.5	0.516	0.866	1.393
B4	***mobile/handheld devices*, *gestures*, *Fitts' Law***, touch screens, text entry, pointing, touch	7	36	43.71	0.470	0.631	3.619
B5	***computer-mediated communication*, *computer supported cooperative work*, *eye tracking***, communication, *empirical study*, *trust*, *videoconferencing*	7	30.71	36	0.496	0.722	2.048
B6	***user studies*, *interaction techniques*, web search**, *input devices*, personalization	5	26.4	28.2	0.442	0.642	1.500
B7	***design*, games, *usability***, user experience, older adults, accessibility, memory	7	30.14	32.14	0.368	0.790	1.476
B8	***children*, *tangible user interface*, multi-touch**, *education*, tabletop, *learning*	6	34	44.16	0.551	0.748	3.333
B9	***evaluation*, *information visualization*, *interaction design***, *participatory design*, assistive technology, *Methodology*, design methods, creativity, *prototypes*, Security, *end-user programming*	11	25.63	27	0.419	0.842	0.855
B10	**social networks, SNS, social media**, twitter, Facebook	5	25.6	34	0.705	0.453	3.700
B11	**crowdsourcing, human computation**	2	23	25.5	0.533	0.268	7.000
B12	***awareness*, *video*, families,** coordination	4	19	23.5	0.690	0.449	2.167
B13	**multitasking, attention, interruption**	3	25.33	31	0.656	0.293	9.000
B14	**emotion, affect**	2	18	24.5	0.792	0.236	6.000

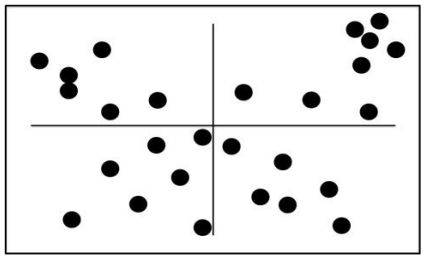
Table 2. Major research themes in HCI during 2004-2013 (size, frequency (F), co-word frequency (CW-F), cohesion, centrality (Centr.), density)

#	Popular Topic (Frequency)	Core Topic (Coreness value)	Backbone Topic (Structural holes)
1	**CSCW** (50)	**CSCW** (0.375)	**CWCW** (42)
2	**world wide web** (35)	two-handed interaction (0.355)	**world wide web** (31)
3	**ubicomp** (28)	**ubicomp** (0.226)	**interaction design** (31)
4	**visualization** (27)	**world wide web** (0.222)	**user interface** (30)
5	input devices (27)	**CMC** (0.191)	**visualization** (29)
6	**user interface** (26)	**information retrieval** (0.186)	input devices (27)
7	**virtual reality** (26)	**infoviz** (0.171)	**interaction techniques** (27)
8	Fitts' law (24)	awareness (0.161)	**CMC** (26)
9	**infoviz** (23)	tangible user interface (0.160)	**ubicomp** (25)
10	**augmented reality** (22)	**virtual reality** (0.160)	**information retrieval** (24)
11	**interaction design** (22)	**user interface** (0.159)	**multimedia** (24)
12	**interaction techniques** (21)	**augmented reality** (0.149)	**infoviz** (23)
13	**information retrieval** (20)	**children** (0.148)	**children** (23)
14	tangible user interface (20)	user studies (0.146)	**virtual reality** (22)
15	**CMC**(20)	**multimedia** (0.145)	Fitts' law (22)
16	**children** (20)	**interaction techniques** (0.142)	Interface design (22)
17	**multimedia** (20)	**visualization** (0.142)	mobile computing (20)
18	user studies (18)	**interaction design** (0.137)	empirical study (20)
19	user interface design (18)	hypertext (0.133)	**augmented reality** (19)
20	cognitive modeling (18)	ethnography (0.113)	agents (19)

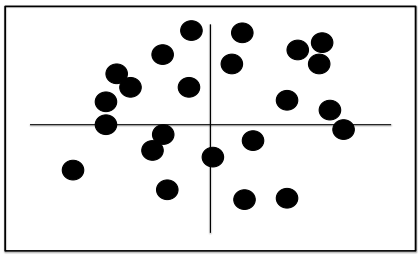
Table 3. Summary of popular, core and backbone topics of HCI in 1994-2003. In bold are keywords that appear in every column.

#	Popular Topic (Frequency)	Core Topic (Coreness value)	Backbone Topic (Structural holes)
1	**mobile phone** (67)	**handheld devices** (0.229)	**ubicomp** (44)
2	**ubicomp** (65)	**gestures** (0.229)	**collaboration** (43)
3	**visualization** (62)	**collaboration** (0.226)	evaluation (43)
4	**handheld devices** (60)	**mobile phone** (0.224)	**mobile phone** (41)
5	**CMC** (59)	**CMC** (0.211)	**children** (39)
6	**gestures** (59)	**ubicomp** (0.210)	**visualization** (38)
7	**user studies** (58)	**CSCW** (0.208)	**design** (38)
8	**collaboration** (57)	touch (0.207)	**gestures** (34)
9	**privacy** (54)	**children** (0.203)	**user studies** (34)
10	**CSCW** (52)	evaluation (0.195)	**CSCW** (34)
11	**design** (49)	**privacy** (0.161)	**CMC** (33)
12	**children** (48)	**user studies** (0.158)	**mobile** (32)
13	sustainability (45)	**design** (0.153)	**handheld devices** (31)
14	ethnography (45)	education (0.152)	**games** (29)
15	evaluation (43)	learning (0.149)	ethnography (28)
16	**infoviz** (43)	**games** (0.146)	**augmented reality** (28)
17	**mobile** (42)	**visualization** (0.146)	social computing (28)
18	**TUI** (38)	**TUI** (0.142)	**privacy** (27)
19	**games** (38)	touch screens (0.134)	**social networks** (26)
20	Fitts' Law (37)	**mobile** (0.134)	mobile computing (25)
21	online communities (36)	tabletop (0.123)	sustainability (24)
22	HCI4D/ICTD (35)	**augmented reality** (0.117)	**infoviz** (24)
23	interaction design (35)	communication (0.116)	education (24)
24	**augmented reality** (34)	**infoviz** (0.115)	learning (24)
25	participatory design (33)	**social networks** (0.113)	communication (24)
26	**social networks** (33)	awareness (0.112)	**TUI** (23)
27	usability (33)	SNS (0.109)	awareness (23)
28	crowdsourcing (32)	wikis (0.106)	participatory design (22)

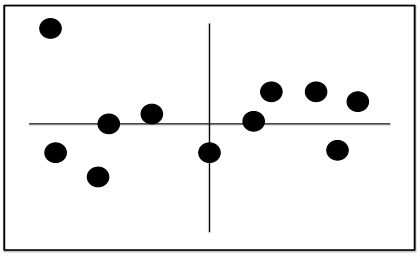
Table 4. Summary of popular, core and backbone topics of HCI in 2004-2013. In bold are keywords that appear in every column.



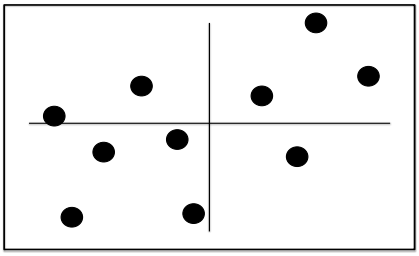
Psychology [21]



Consumer Behavior [22]



Software Engineering [11]



Stem Cell Research [1]

Figure 5. Indicative strategic diagrams from other scientific disciplines.

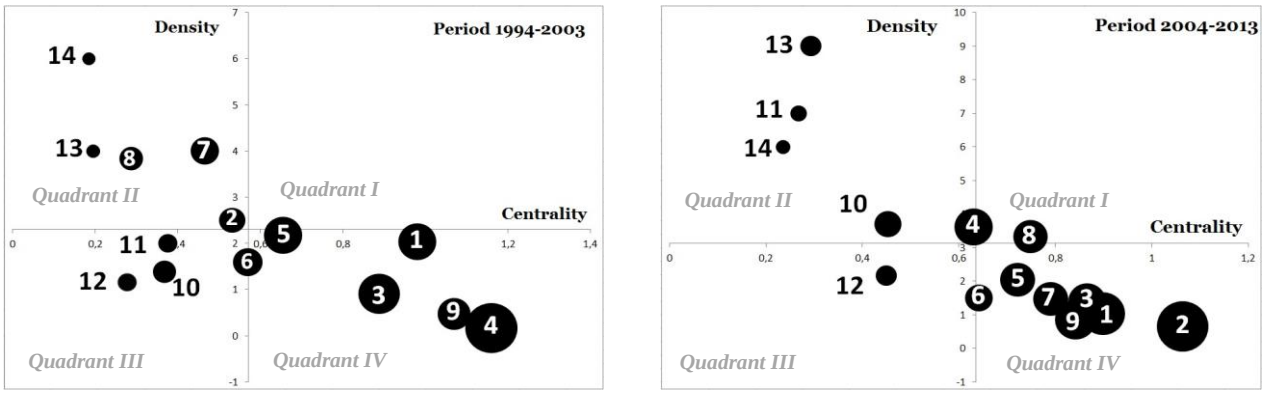


Figure 4. Strategic diagram for CHI for the period 1994-2003 (left), and 2004-2013 (right).

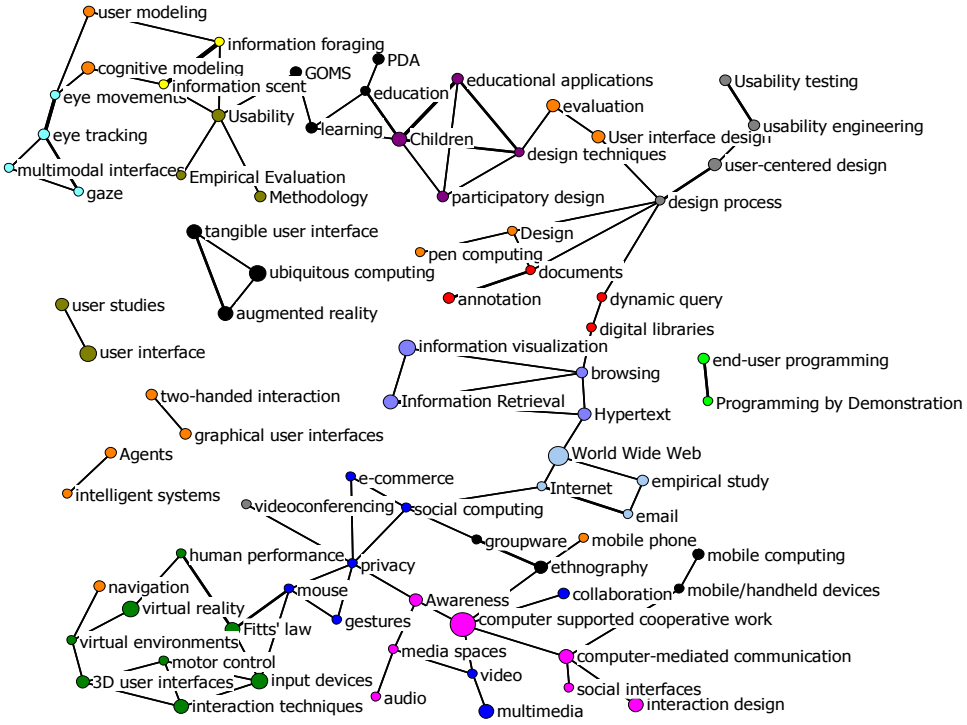


Figure 6. Keywords networking map 1994-2003 (the line represents the link between two keywords with correlation coefficient ≧ 0.14). An interactive version of this graph is available at http://goo.gl/BAjyMt.

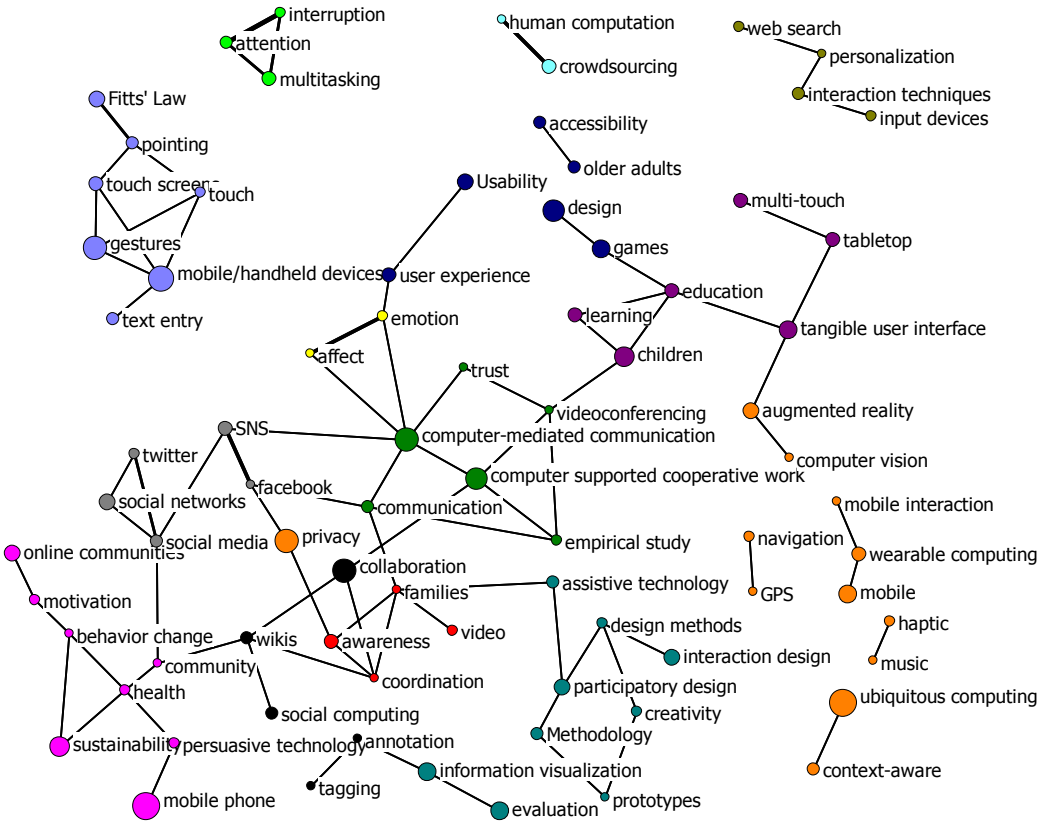


Figure 7. Keywords networking map 2004-2013 (the line represents the link between two keywords with correlation coefficient ≧ 0.09). An interactive version of this graph is available at http://goo.gl/v8j1Nh.

DISCUSSION

Underlying trends within HCI

While previous work [16] has outlined major paradigms within the field of HCI, our work provides a novel perspective towards seeing the big picture within our discipline. Our analysis has identified a number of research themes that are based on the co-presence of keywords on published papers – as opposed to a tacit interpretation of the field and its methods. Thus, our findings reflect the research that was *actually* conducted and published, not how a researcher would subjectively or intuitively map the field. Orthogonal to this analysis we add the dimension of time, and focus on analyzing our field in two distinct periods. This gives us the benefit of hindsight when interpreting our findings for the first period (1994-2003), since we are able to validate our claims for that period on the subsequent period of analysis.

1994-2003

In **Figure 4a**, quadrant II, we observe clusters A2 (www), A7 (hypertext), A8 (children), A13 (end-user programming) and A14 (information foraging) have a high density but low centrality. This indicates that these research topics are fairly isolated from other research topics but internally well connected. In particular, research in clusters A13 and A14 is less popular, and in hindsight we observe that in period 2004-2013 these clusters have disappeared.

In quadrant III, clusters A6, A10, A11 and A12 exhibit low centrality and density. These are indicative of research topics that are either emerging or fading, with a higher likelihood of change. In hindsight we can identify that one of these clusters was actually fading (A12: digital libraries), while the other three emerging (A6: methodology, A10: user-centered design, A11: eye tracking).

In quadrant IV, clusters A1 (CSCW), A3 (ubicomp), A4 (visualization), A5 (UI design) and A9 (multimedia) have high centrality but low density, sign of an important yet immature research topic in the field. Their importance is evidenced by the frequency in which the keywords appear, often leading to more concrete research subfields. In hindsight, new conferences were spun-off from these clusters: Ubicomp in 2001 and Pervasive in 2003 (from A3), and IUI in 1997 (from A5).

Surprisingly, we found no research topics in quadrant I, *i.e.*, with a high centrality and density. Closest to quadrant I we found cluster A5 (input devices, virtual reality, information visualization), with a high centrality, reflective of an important area for CHI as a conference and HCI as a field in the early days of computer-human interaction.

2004-2013

In **Figure 4b**, in quadrant I we find B8 (children, tangible user interfaces, and multi-touch), the maturing theme relating to children and learning through the use of tangible and tabletop technologies. Our analysis suggests that these themes are likely to become motor themes in the future.

In contrast, located in quadrant II are clusters B4, B10, B11, B13 and B14, clusters with high density but low centrality, well-focused and developed research topics, yet fairly isolated from other research topics. Some of these themes focus on relatively recent technology and trends (*e.g.*, B11: crowdsourcing, B10: social networks, B14: emotion & affect) that have not had time to establish strong ties to other research themes. Yet some of these themes represent more traditional work that has remained relatively isolated (B4: text entry & Fitt's law, B13: multitasking).

In quadrant III we expect clusters that are emerging or fading. Here we find theme B12 (awareness, video), which is most likely a fading theme judging by its relatively small frequency.

Finally, themes in quadrant IV are likely to be core and transversal for HCI. Here we find multiple clusters (B1, B2, B3, B5, B6, B7, and B9) of high frequency. Given that these large clusters have low density, they are evidence of field expansion during this time period. We note that in the period 1994-2003 new conferences emerged from themes in this quadrant that went on to become mainstream, and so we may expect the same from these themes here.

Trending topics

Next, our analysis focused on specific topics or keywords. A limitation of our previous analysis was that some of the research themes contained multiple and diverse keywords, making it hard to precisely characterize each theme. Here we overcome this challenge by conducting a core-periphery analysis of individual keywords to more precisely map their role and evolution over time.

1994-2003

For the period 1994-2003, 14 of the 20 keywords appear as popular, core and backbone topics *simultaneously* (**Table 3**, in **bold**). This indicates a consistency between research interests, knowledge acquired, as well as effort to maintain the field. In contrast, the research topics of "*tangible user interface*" and "*user studies*" are popular and core topics, but have a relatively low number of structural holes. This indicates that whilst these research topics have the potential to prosper the field, they are not the '*backbone'* during the period.

As yet another example, research topics of "*input devices*" and "*Fitts' law*" are popular and backbone topics, but are not core topics, indicating that research on these topics has not yet effectively extended the knowledge landscape of the field. Interestingly, research topics of "*mobile computing*," "*empirical study*" and "*agents*" were not popular or core research topics, but they played an important role in bridging different research efforts to establish an internally cohesive research field of HCI (*i.e.*, higher structural holes count).

Lastly, despite the research on "*two-handed interaction*," "*awareness*," "*hypertext*" and "*ethnography*" effectively extending the HCI knowledge scope (*i.e.*, high core and structural holes count), a limited attention was given to these research topics (*i.e.*, low popularity).

2004-2013

Compared to the period of 1994-2003, we identified a higher number of keywords (N=28) as core research topics for the period of 2004-2013, indicating growth of the knowledge field of HCI (**Table 4**). Of the top 28 keywords, 18 keywords were simultaneously popular, core and backbone topics (**Table 4**, in **bold**). "*Sustainability*" and "*ethnography*" are both popular and backbone research topics, however not core topics. "*Education*," "*learning*,"

"*communication*" and "*awareness*" are both core and backbone research topics, but not hot topics. These results suggest that an increased attention towards these topics is required in order to develop and maintain the development of the field.

Many keywords are found to exist only in one group: "*Fitts' law*", "online *communities*," "*HCI4D/ICTD*," "*interaction design*," "*usability*," "*crowdsourcing*," "touch," "*touch screens*," "*tabletop*," "*SNS*," "*wikis*," "*social computing*" and "*mobile computing*." These keywords indicate a *paradigm change* in the field, as they disappear or emerge. In addition, despite their popularity, if the keywords are neither in the core or backbone topics, they are potentially a mismatch of research efforts.

In summary, comparing the popularity of the keywords between the two periods, *only* 42 of 94 keywords (44.7%) between 1994-2003 are found again as top keywords between 2004-2013 (italic font in table 2). In other words, most top research topics of the first ten years were *replaced* by new research topics in recent years. The whole field witnessed a *paradigm change* during this period.

Fluxionary Research

The field of HCI grew considerably in the last 10 years, from an average of approximately 70 (1994-2003) to 245 publications per year (2004-2013). We observed an overall increase in research clusters' centrality (from 0.571 in 1994-2003 to 0.635 in 2004-2013), and density (from 2.305 in 1994-2003 to 3.127 in 2004-2013) (Figure 4a and Figure 4b, respectively). This means that HCI is becoming increasingly cohesive. However, the field is lacking a major driving theme that could potentially accelerate this process, but instead consists of multiple themes competing for recognition despite cooperating with each other.

While the underlying dynamics of themes point to gradual maturity, the field has witnessed a recent explosion in the number of specific topics or keywords. Overall keyword centralization has decreased from 31.04% in 1994-2003 to 26.79% in 2004-2013, indicating that the leading research keywords are constantly becoming less central in the network. This is inevitable given that more new research connections have been established between different research topics in the later ten years.

For example, our analysis reveals that "social networks" and "crowdsourcing" are completely new research themes established during 2004-2013, located in quadrant II, clusters (B10, B11) (**Figure 4b**). However, this should not come as a surprise if the reader takes into account the emergence of several social networking web sites during this period (*e.g.*, Facebook and Twitter opened to the general public in 2006, Google+ in 2011). Similarly, crowdsourcing presents itself as an emerging research theme in 2004-2013 even though the first publication with this keyword only appeared at CHI in 2009. However, due to its rapid growth it has in merely 4 years positioned itself as an important emerging research paradigm despite its low centrality and therefore weak connection to other research paradigms. During the same time period, in clusters B13 and B14, "multi-tasking" and "emotion" are hand-in-hand with the highest density. This indicates a cluster that contains "inseparable" expressions that are usually co-present, much unlike the previous cluster in which, more often than not, only one of those keywords appear.

In parallel to the emergence of research themes, there are others that *decline* or *merge*. For instance, "End-user programming," and "information foraging," from clusters A13 and A14, have faded from the landscape of HCI research as major independent research subfields.

A theme can also merge with others for several reasons, such as the introduction of novel technology leading to appropriation, or because a new advance is beneficial to both fields. For example, in the early days of CHI, "annotation" from A12 took form in physical documents. With the availability of collaborative tools, such as "wikis", and social "tagging" (from cluster B3), annotation is now in the context of digital formats. Another example is the merging of "computer supported cooperative work" from cluster A1 with "eye tracking" from cluster A11 resulting to cluster B5 in 2004-2013, as eye-tracking methodologies began to be used in collaborative settings, such as [23].

Research themes merging can lead also to new research topics: "ubiquitous computing," "augmented reality," and "ethnography" (from A3) and "visualization," "user interface design," and "cognitive modeling" (from A4) triggered the creation of three novel subfields: "mobile phone," "sustainability" and "ethnography" (B1); "ubiquitous computing," "privacy" and "mobile" (B2); and "visualization," "collaboration" and "user interface" (B3). Research on the older topics is now intertwined with these new topics, contributing to the appearance of several research directions like sustainability [4], large-scale ethnography [12] and ubiquitous public displays [15,19].

Where is the accumulated knowledge?

As it stands, the only tradition in HCI is that of having no tradition in terms of research topics. HCI has a long enough history for knowledge to accumulate, but to what extent has this happened? Do prior studies help us when it comes to new technologies? Judging from our findings the answer is no, when a new technology comes along it seems that researchers start from scratch leading to relatively isolated research themes. There seems to be no single well-defined way to study a new technology in the context of HCI. As a result, different approaches or perspectives are adopted when studying a new technology, leading to a relative fragmentation within HCI.

Reflecting on our own experience, we believe that the accumulated knowledge in HCI is almost exclusively grounded on very specific technological contexts. For instance when it comes to improving the design of a mouse, previous studies on ergonomics are helpful. But when the mouse is replaced by a touch-screen or voice input, previous findings on mouse performance tend to be inapplicable. This is not an HCI phenomenon: the transition from gramophone to music tapes to CDs to iPods had a similar effect on multiple disciplines. Due to the rapid pace of technology designed for humans, however, knowledge in HCI tends to be highly contextual instead of universal like in the field of biology or physics. So we argue that by nature HCI research is like nomads chasing water and grasslands, making it challenging for the community to accumulate knowledge.

Of course, the Human in HCI does not change as rapidly as technology, even though practices and habits do. Hence one potentially solid ground for HCI to develop accumulated knowledge is on the human aspects of HCI, and this was acknowledged in the session "celebrating the psychology of human-computer interaction" in CHI 2008 [2]. However, our analysis shows that this is far from likely to happen in the community, with no discernable research theme emerging on this topic.

Note that a motor theme should be derived from well-established knowledge (high density), and have implications to new HCI topics (high centrality). Therefore, the existence of accumulated knowledge that is applicable to the context of new technologies is an important condition for the formation of motor-themes. Based on the above discussion, we believe that the 'nomads' nature of HCI research largely contributes to the lack of motor theme in the field.

Should CHI break up into multiple conferences?

The diversity of the CHI conference, and more broadly of the HCI field, has often prompted discussion. The diversity of the papers submitted to the CHI conference often backfires when authors feel that their work is not evaluated by 'true' experts, or indeed by someone of an appropriate background. Furthermore, researchers complain that some kind of work is "more valued", specifically raising the issue of one-off novelty experiments being preferred over laborious system development. On the other hand, researchers feel that the diversity of the field is one of its key strengths. Thus, the issues of rigor, diversity, and reviewing process become intertwined in discussion. We attempt to relate our findings to this discussion and shed some light on the underlying processes of our discipline and how we should approach rigor and diversity.

First, our results show that HCI *is* a diverse field. However, the field is diverse not in the sense that it consists of multiple disconnected research themes, like a pot-pouri, but in the sense that there are a lot of links within and between diverse themes, rather like a cobweb. In fact, only a handful of clusters fall in Quadrant II (isolated themes) in Figure 4, with most large clusters falling in Quadrant IV (transversal themes) indicating an expansion of the field.

Our results also show that over time, the themes *have* become more cohesive, while at the same time there is a much larger number of topics or keywords in the discipline. To a large extent, this is stimulated and driven by factors external to the community, for instance through the introduction of new technological products and services (*e.g.*, iPhone, Facebook) that have a direct impact on humans' life. As technology advances, and the rate of innovation remains high, we can expect this trend to remain: more new topics will constantly be of relevance to the HCI community.

The key insight we obtain from our results is that any breakup of the CHI conference today, or the HCI field, is likely to be pointless in a few years. The community simply lacks the motor themes along which a potentially meaningful break up could be achieved (Quadrant 1 in Figure 4). Our community is slowly maturing in terms of themes, but is not transversally mature and the recent expansion of topics is likely to delay this process.

A further insight from our analysis attests to the value of diversity in our community. We identify many instances where topics merge or interact with each other in unpredictable ways, sometimes establishing new themes, sometimes declining. This strong interaction is indicative of the adaptability of our community, constantly evaluating alternative approaches and attempting to conquer new ground. A break up of the community would only hinder this process, making it much harder to cope with the introduction of new topics. This diversity and constant state of flux is crucial in assimilating and dealing with new topics.

The polycentric nature of the knowledge map of HCI, as opposed to a unicentric one, reveals a key property of our community. Our analysis of the keywords making up the various clusters suggests that when a new technology is introduced, our community tackles it and approaches it from a number of perspectives. For instance, the introduction of tabletop technology prompted usability and Fitts' law studies, studies on security and privacy, studies on education and learning. Similarly the introduction of smartphones and social media has been tackled from multiple perspectives. This pluralism is a characteristic of our community, for better or worse.

In summary, our analysis suggests that the HCI community:

- is having to deal with an increasing number topics that are externally driven (*e.g.*, new products, services, advances in other sciences);
- is responding to this challenge by maintaining a diverse yet intertwined research profile which remains in flux;
- is gradually maturing in terms of its themes, but it is simply not transversally mature enough to undergo a meaningful breakup.

LIMITATIONS

We considered only a single source of publications, the CHI conference, which despite being the flagship conference of the discipline has a strong geographical bias with most papers coming from the US, UK and Canada [2]. The fact that no journals were included in our analysis means that work on topics more likely submitted directly to journals is likely to be underrepresented in our sample.

Furthermore, the CHI conference has an acceptance rate of about 24%, so most papers that were submitted to CHI were eventually published somewhere else – and therefore not included in our sample. Finally, a crucial issue is the extent to which keywords accurately reflect the contents of a paper. It is not clear whether all authors follow the same approach for assigning keywords to their papers, and this is likely to lead to some inconsistencies. Also, it is possible that some change of keyword frequency may come from a change in practices of how authors assign keywords. However most of the keywords refer to specific technologies, rather than generic concepts that can be used interchangeably due to authors' habit. So we feel that it is very unlikely that the change of major keywords during the two periods comes from authors' habits.

CONCLUSION

In summary, our findings suggest that the field of HCI has undergone dramatic change in the past 20 years. We can see a clear paradigm change from the top keywords list, more than half of which in 1994-2003 have disappeared from the

top list of 2004-2013. No research theme seems to be immune from the influence of evolution. Rapid technology change, including the prevalence of mobile devices and technologies and the availability of new service like SNS and crowdsourcing appear as a sort of driving force.

From the perspective of the whole network, the study reported an enhanced cohesion of the field. The overall network density increased while the whole network became more internally connected. This implies progress towards the formation of a concrete research field of HCI as a whole. However, the results also indicate unmatched research efforts on hot, core and backbone topics in recent years, suggesting an ongoing and rapid paradigm shift.

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