

# The Intellectual Structure of Human Computer Interaction Research

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Although human-computer interaction (HCI) has been developing for thirty years, the field has advanced slowly due to a lack of knowledge about HCI structure. This research thus seeks to explore and clarify HCI intellectual structure. Data collected from the ISI Web of Knowledge totaled 1,168 HCI related articles, and 33,724 references were identified. There were 75 highly cited research articles identified using a citation analysis and then implementing co-citation analyses, including factor analysis, multidimensional scaling and cluster analysis. According to cluster analysis, twelve core knowledge domains of HCI were identified: System capability, User interface design, Task of the HCI system, Evaluation of interaction, User acceptance of technology, Personalized system design, Interface analysis, Performance measurement and improvement, Development of interaction, Human reaction to technology, Facial expression, and Effective interaction. Among these topics, two of them, “Personalized system design” and “Facial expression”, are new intellectual cores which did not appear in previous related researches. The findings of this study provide an intellectual structure and research directions for researchers and practitioners interested in the HCI field.

**Keywords:** *Human-computer interaction, Factor analysis, Citation analysis, Co-citation analysis*

# 1. INTRODUCTION

Until late 1970s, no one could interact with computers except for computer experts. This situation changed entirely after personal computing, including both personal software and personal computer platforms, was developed, which turned everybody into a potential computer user [1]. The development of the field of Human-Computer Interaction (HCI) soon followed. With the rapid growth of information systems and communication technology, information technology has come to play a central role in our daily lives. Issues regarding the interaction between humans and computers have thus become important and fundamental [2]. The study of HCI has become a main theme in academic and empirical studies and has attracted much research attention. Nowadays, across the globe one can find many specialist journals (Human-Computer Interaction, International Journal of Man-Machine Studies, Behavior and Information Technology, International Journal of Human-Computer Interaction, Interacting with Computers) and specialist conferences (ACM CHI Human Factors in Computing Systems Conference, ACM User Interface Software Technology Conference, British Computer Society (BCS) HCI Specialist Group (SG) Human-Computer Interaction Conference, International Federation for Information Processing (IFIP) INTERACT Human Factors in Computing Conference, International Conference on Human-Computer Interaction) [3].

The field of HCI was formally founded in 1982 [4]. In the early stage of HCI in 1970~80s, HCI was about how users interacted with office automation programs, such as word-processing and databases. The focus was on basic interactions, such as dialog boxes and error messages. During the late 1980s, the graphical user interfaces started to rise to prominence, and usability engineering methods were developed. In the 1990s, a major shift in the field of HCI research occurred as the internet and the web applications became widely used, such as web page, e-mail, instant messaging. New types of interfaces and communication research were needed. Around 2005, the focus shifted more toward user-generated content, such as photos, videos, and blogs, with an emphasis on collaboration, connection, emotion, and communication. By the 2010s and the rising popularity of portable devices, mobile and wearable computing and enjoyable usage has become the center of attention.

The field of HCI integrates many different disciplines, and researchers have differing and competing views on HCI, often disagreeing on even what “real HCI research” means [4]. Therefore, although HCI articles abound, there are a diversity of definitions and topics. Although many textbooks and articles have tried to classify the topics in the HCI field, many of the categories were based on subjective observation, and few classification attempts provided clear evidence about their classification, which may not indicate an intelligent structure within topics. Therefore, in this research, a data-driven approach which provides objective and quantitative data to derive an intellectual structure from the academic literature for research trends and issues is required.

The bibliometrics, were used to detect the areas in research networks objectively and to assess the interactions between fields [5]. One of the well-known bibliometrics methods is co-citation analysis [6]. The co-citation analysis was used to understand the similarity of content between two documents by counting the number of documents which have been cited in a pair [5, 7]. Since the bibliographic references of a paper are often considered to be the signal of their influences in the development of research, they could be used to identify networks of documents belonging to the same discipline by analyzing the references [8].

The goals of this research are in line with the co-citation method: (1) explore the key content of the HCI knowledge, and (2) identify the intellectual cores that have emerged within HCI research. The intellectual structures are analyzed and mapped graphically, and the main trends within HCI can be recognized. The remainder of the paper is organized as follows. The next section reviews the HCI and the co-citation literature. The third section presents research methodologies, including citation analysis, co-citation, factor analysis, multidimensional scaling, and cluster analysis. The fourth section shows the results of the data analysis and discusses the key findings of this research. The fifth section includes the conclusion of the study, its limitations, and future areas of study.

## 2. RELEVANT RESEARCH

### 2.1 Human-computer interaction

The rise of the field of HCI in the 1980s was a response to the popularity of personal computing [4]. Until now, it has been developed more than thirty years and had become one of the five main research streams in MIS discipline [9]. HCI is a field integrated from several disciplines [4], and more disciplines are involved as the HCI field continues to develop [4]. In the early stages, HCI was a field of research initially in computer science related to cognitive science and human factor engineering [1]. Hewett, et al. [3] described it as four main disciplines: computer science (application design and engineering of human interfaces), psychology (the application of theories of cognitive processes and the empirical analysis of user behavior), sociology and anthropology (interactions between technology, work, and organization), and industrial design (interactive products). HCI has also been declared as a study of the communication between a human and a machine, drawing on supporting knowledge on both the machine and the human side. On the machine side, relevant factors include techniques in computer graphics, operating systems, programming languages, and development environments. On the human side, communication theory, graphic and industrial design disciplines, linguistics, social sciences, cognitive psychology, social psychology, and human factors such as computer user satisfaction are relevant. Also, engineering and design methods are involved [3]. Concerning its relation to other MIS streams, the HCI stream emphasizes the individual-level human cognitive bases for effective systems design, and the openness of human decision makers to accept the recommendations of systems [10].

Due to the multidisciplinary nature of HCI, it is also named human-machine interaction (HMI), man-machine interaction (MMI) or computer-human interaction (CHI). This diverse situation also applies to the definition of HCI, and there is no agreed upon definition of HCI from the range of disciplines [3, 11]. Hewett, et al. [3] defined HCI as “a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them”, and Zhang, et al. [9] described HCI as being “concerned with the ways humans interact with information, technologies, and tasks, especially in business, managerial, organizational, and cultural contexts”. The core element of these definitions is the concern about humans, not only relating to the interest in human psychological reactions, but also the human interactions with technologies for different purposes [2].

There have been several major shifts concerning HCI development. In the 1970s, the topic was mainly about the office automation, and in 1980s, graphic user interface was the main topic. Newell and Card [12] declared that psychology played an important role in HCI development. Lewis [13] proposed the understanding of goals and preferences, thereby broadening applied cognitive theory, and supporting innovation. In the 1990s, usability engineering method caught researchers' attention, for which the design of HCI was an important part. Bodker [14] proposed a HCI design framework, and Ritter and Larkin [15] presented a computer-supported methodology for developing models. By the 2000s, the HCI field matured, and many more theories and perspective implemented in this field. McFarlane and Latorella [16] identified human interruption as an important issue for HCI, and provided approaches for interface design to help users effectively manage interruptions. Tung and Chan [17] facilitated the development of relevant HCI design guidelines for Complex socio-technical systems (CSTS).

In the past, research focused on specific elements and seldom outlined an updated overview picture of the HCI sub-fields. Researchers surveyed the HCI area, but they only applied particular components, such as the visual interpretation of hand gestures [18], examination of the usability of evaluation methods [19], age-differentiated design of HCI [20], review of human vocal emotion and simulation [21], and the exploration and study of visualization in the HCI [22]. Compared with these specific researches, few articles have tried to focus on the comprehensive structure. Zhang [2] directed HCI studies on MIS from a top down perspective, and Grudin [23] provides a comparison between MIS, Human Factor and HCI. A data-driven view based on MISQ and the ISR journal was also accessed [11]. Preece, et al. [24] outlined the factors in HCI as productivity factors, system functionality, constraints, task factors, user interface, health and safety factors, the user, comfort factors, organizational factors, and environmental factors. The ACM SIGHCI [3] presented a framework, in which HCI was classified into the categories of Use and Context of Computers, Human Characteristics, Computer System and Interface Architecture, and Development Process [2] Zhang, et al. [9] developed a framework of broad HCI issues, which consisted of three categories: IT Development, IT Use and

Impact, and General Research Topics. There are two major approaches that researchers have applied to empirically access the intellectual development of the IS field. The first classifies by code categories of interest, typically topics and methods. The second approach uses citation analysis to examine the references of cited articles [2, 23]. These approaches can be extended for application to HCI as well. Zhang and colleagues' research [2, 9, 11] applied coding techniques for classification, where the articles were independently and manually coded by several researchers with pre-defined classifiers that were developed using surveys or keywords [2, 23]. However, the drawback of this coding classification technique for topics is that it may not be easy to discover a new trend at the beginning stage of the sub-field, and may overly focus on the mature sub-fields. For example, Zhang et al. [9] developed three main categories, but the classification results showed that the most popular topics accounted for 83.3% and fell into one category (the IT Use and Impact category), whereas the other two categories contained less than 20% (12.2% for IT Development and 4.6% for General Research Topics). This finding shows that the topic classification according to the pre-defined classifiers of HCI may not clearly indicate the research interest and development trends. Therefore, in this research, the data-driven citation analysis approach was applied for developing the classification, and the results from different approaches were compared in order to bridge the knowledge gap.

## 2.2 Co-citation analysis

Bibliographic citation analysis is a measurement showing the relationships between reference documents, such as bibliographic coupling and co-citations [5]. In the present research co-citations were applied, the subfields and core research areas of HCI were identified. Co-citation analysis can provide objective and quantitative data to meet these goals. Co-citation data can be considered as linkage data among documents/articles, while cited references are variables attributed to documents/articles. From a network perspective, the researchers may focus on how the network develops structurally over time [25]. There are various types of co-citation analysis: document co-citation analysis, author co-citation analysis, and journal co-citation analysis. Document co-citation analysis evaluates the network between documents which are linked according to their joint citations [5]. Author co-citation analysis is applied to authors instead of documents to produce maps of prominent authors within a selected field [26, 27]. Journal co-citation analysis views key journals of each field as the units of analysis [28, 29].

Small [5] introduced the document co-citation analysis method and defined it as a measurement showing the degree of relatedness between documents as perceived by the population of citing authors. The method assumes that bibliographic citations are an indicator for the actual influence of various information sources on a research project [30]. A document with a high citation rate reflects high peer recognition [31]. Since highly cited documents represent the key concepts, methods, or ideas in a field, then the co-citation patterns can explain in great detail the relationships between these key ideas [5].

A number of researchers in different fields have demonstrated that the co-citation method is a valid approach to explore the intellectual structure, such as Culnan's [32] exploration of the knowledge structure of management information systems (MIS) from 1980 to 1985, and comparison with early studies. Sircar, et al. [33] explained the evolution of structured and object-oriented systems methodology. Tight [34] conducted research in an educational research community, identifying community practices. Casey and McMillan [35] investigated the research topics of industrial and labor relations. Pilkington and Meredith [36] implemented the co-citation method in Operations Management in order to obtain the knowledge structure at different time periods. Hsiao and Yang [8] developed the knowledge structure of the technology acceptance model (TAM). Shiao and Dwivedi [37] researched the knowledge structure and trends in the field of e-commerce.

### 3. METHODOLOGY

#### 3.1 Research flow

In this study, a research flow was proposed to discover the intellectual structure of HCI. The first step was to collect source articles related to HCI by using the ISI Web of Knowledge. The keywords (of “human-computer interaction” or “computer-human interaction”) were searched for a limited range of article types and time period. Then the amount of related articles and their references were identified. Secondly, by applying citation analysis, the highly cited articles were obtained. Thirdly, the co-citation method was applied to generate a highly cited co-citation matrix. Finally, this matrix was evaluated using the methods of factor analysis, cluster analysis and multidimensional scaling, which resulted in the classification of these articles. These classes represent the intellectual core of HCI.

#### 3.2 Selection of source articles

The research articles comprising this research were collected from the Institute for Scientific Information (ISI). The ISI database is famous and has an excellent reputation. It is an online citation database containing more than 10,000 highly influential journals. This database contains three different sections: the Arts & Humanities Citation Index (A&HCI); the Science Citation Index Expanded (SCI-EXPANDED); and the Social Sciences Citation Index (SSCI). Concerning HCI research, research from Lazar et al.[4] provided two related keywords: “Human-computer interaction” and “Computer-human interaction”. These two keywords were applied to searches that were limited to only the fields of Topic and Article, and only SCI-EXPANDED and SSCI were included. This resulted in the collection of 1,968 articles and 33,724 citations.

#### 3.3 Citation analysis

Citation analysis is applied to access a huge amount of information in order to understand the trends of a research issue for a particular discipline [38-40]. Examples of this include when the major articles in the field were written, how their popularity fared over the time period, and whether the article is still useful today for current researchers. The citation rates are applied to determine the major field directions and the undergoes direction changes [36]. In this research, citation analysis was applied to identify highly cited articles. It is generally assumed that a highly cited research article is especially valuable.

#### 3.4 Co-citation analysis

The Co-citation analysis method is a famous structuring analysis method [6], based on counting the amount of paired cited documents in the same article[5, 41]. When 2 documents, A and B, are simultaneously cited in article X, the pair AB is weighted as one. Moreover, if the pair documents A and B is also cited in another article Y, then the weight of pair AB becomes two, etc. Therefore, through the relevant cluster analyses, the structure of scientific knowledge in the specific field can be developed [42], and the primary topics can be identified. Since all articles are recoded according to the degree of correlation, the data are converted to achieve standardization. The conversion methods could apply Pearson correlation coefficients, cosine coefficient, and squared Euclidean distance. The methods such as factor analysis, cluster analysis, and multidimensional analysis can be implemented to analyze this standardized co-citation matrix [43]. According to the research of Hsiao and Yang [8], the amount of co-citation articles should more than 30.

##### 3.4.1 Cluster analysis

Cluster analysis is a multivariate technique aims to classify data according to the characteristics

that users select. In each cluster, it should exhibit strong internal (within-cluster) homogeneity and high external (between-cluster) heterogeneity [44]. When plotted geometrically, the members within clusters are situated close together and are far apart between different clusters. In this research, Ward's method was applied as the clustering algorithm in accordance with the minimum increase of the total sum of square across all members in all clusters [37, 44]. Cluster analysis applied to the co-citation matrix can cluster relative articles [45], indicating indirectly the core group knowledge of the research area.

### 3.4.2 Multidimensional scaling

Multidimensional scaling (MDS) is a procedure displaying data graphically and allows users to determine the perceived relative image in a set of data. Therefore, it is also known as perceptual mapping. The goal of MDS is to transform data similarity into distances represented in multidimensional space. In this study, the citation matrix of research articles was through a squared Euclidean distance conversion, and presented on a two-dimensional graph. Each article was represented as a point on this two-dimensional graph, with a shorter distance between two points indicating a higher degree of correlation between the two articles [25]. The research of Hair [44] suggests that the stress pressure of selected articles should less than 0.2.

### 3.4.3 Factor analysis

Factor analysis is a technique that analyzes the correlations among a large number of variables, constructs the maximize interpretation of variables, and performs data summary and data reduction. Factor analysis is commonly applied in co-citation analysis [25, 32, 46]. It is assumed that important articles tend to cite research concepts that are normally be co-cited by articles within a specialized research area [45]. These articles quite often are loaded in the same factor, where every factor represents an intellectual core of the research area [47]. Past research [8, 48] has pointed out that the total variance explained in factor analysis have to be higher than 70%.

## 4. RESULTS AND DISCUSSION

Following the aforementioned research procedural flow, 1168 HCI research articles and 33,724 references from the ISI web were identified. The citation analysis was applied to obtain the highly cited articles and generate a co-citation matrix. The stepwise detection method was applied as a response to the abovementioned limitations such as stress pressure, minimum amount of articles, total variance explained of all articles and perceptual observation. Seventy-five highly cited articles were identified. Then, applying the factor analysis method, cluster analysis and multidimensional scaling (MDS) were used to identify the intellectual core of HCI among these articles [25, 32, 46]. Finally, hierarchical cluster analysis was implemented to determine the merging core knowledge. The results and discussion are illustrated in more detail in the following.

### 4.1 Citation

This research counted article citation frequency from ISI. The aforementioned conditions were satisfied: the total variance explained in factor analysis has to be higher than 70% [8, 45, 48], and the stress pressure of selected article should be less than 0.2 in multidimensional scaling. Therefore, articles cited more than 16 times were selected as the threshold. In total, 75 articles were selected as the highly cited articles and shown in Table 1. Then each of highly cited articles was paired with each other articles within this set and formed a 75x75 square co-citation matrix. This matrix then was transformed into Pearson's correlation matrix.

**Table 1** Highly cited articles

No	Author	Journal	No	Author	Journal
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No	Author	Journal	No	Author	Journal
1	Pavlovic, et al. [18]	IEEE Transactions Pattern Analysis Machine Intelligence	39	Cohen, et al. [49]	Computer Vision and Image Understanding
2	Davis [50]	MIS Quarterly	40	Payne et al.[51]	Human-Computer Interaction
3	Fitts [52]	Journal of Experimental Psychology	41	Soukoreff et al.[53]	IJHCS
4	Cowie, et al. [54]	Signal Processing Magazine, IEEE	42	Picard et al.[55]	Interacting with Computers
5	Pantic et al.[56]	Proceedings of the IEEE	43	Murray and Arnott [21]	The Journal of the Acoustical Society of America
6	Nass et al.[57]	Journal of Social Issues	44	Fornell and Larcker [58]	Journal of Marketing Research
7	Davis et al.[59]	Management Science	45	Russell [60]	Journal of Personality and Social Psychology
8	Miller [61]	Psychological Review	46	Ghani et al.[62]	Journal of Psychology
9	Nass et al. [63]	IJHCS	47	Agarwal and Karahanna [64]	MIS Quarterly
10	Nass, et al. [65]	IJHCS	48	John and Kieras [66]	ACM Transactions on Computer-Human Interaction
11	Weiser[67]	Scientific American	49	John and Kieras [68]	ACM Transactions on Computer-Human Interaction
12	MacKenzie [69]	Human-Computer Interaction	50	Lang [70]	American Psychologist
13	Rabiner [71]	Proceedings of the IEEE	51	Dey et al.[72]	Human-Computer Interaction
14	Essa et al.[73]	PAMI, IEEE	52	Wren, et al. [74]	PAMI, IEEE
15	Moon et al. [75]	Communication Research	53	Rowley et al.[76]	PAMI, IEEE
16	Yang et al.[77]	PAMI, IEEE	54	Johnson et al.[78]	International Journal of Artificial Intelligence in Education
17	Venkatesh et al.[79]	MIS Quarterly	55	Lavie and Tractinsky [80]	IJHCS
18	Pantic et al.[81]	PAMI, IEEE	56	Davis [82]	International Journal of Man-Machine Studies
19	Fasel et al.[83]	Pattern Recognition	57	Fischer [84]	User Modelling and User-Adapted Interaction
20	Fogg and Nass [85]	IJHCS	58	Weizenbaum [86]	Communications of the ACM
21	Scheirer et al.[87]	Interacting with Computers	59	Trevino and Webster [88]	Communication Research
22	Hoffman et al.[89]	Journal of Marketing	60	Sundar and Nass [90]	Communication Research
23	Venkatesh et al.[91]	Management Science	61	Dowell and Long [92]	Ergonomics
24	Gray, et al. [93]	Human-Computer Interaction	62	Gray and Salzman [19]	Human-Computer Interaction
25	Picard, et al. [94]	PAMI, IEEE	63	Sproull, et al. [95]	Human-Computer Interaction
26	Hudlicka [96]	IJHCS	64	Sturman and Zeltzer [97]	Computer Graphics and Applications, IEEE
27	Nass, et al. [98]	IJHCS	65	Starner, et al. [99]	PAMI, IEEE
28	Kieras and Polson [100]	International Journal of Man-Machine Studies	66	Vicente et al.[101]	Systems, Man and Cybernetics, IEEE
29	Tractinsky, et al. [102]	Interacting with Computers	67	Taylor and Todd [103]	Information Systems Research
30	Abowd and Mynatt [104]	ACM Transactions on Computer-Human Interaction	68	Isard and Blake [105]	International Journal of Computer Vision
31	Venkatesh [106]	Information Systems Research	69	Hornbæk [107]	IJHCS
32	Klein et al.[108]	Interacting with Computers	70	Polson, et al. [109]	International Journal of Man-Machine Studies
33	Larkin and Simon [110]	Cognitive Science	71	Fitts and Peterson [111]	Journal of Experimental Psychology
34	Webster, et al. [112]	Computers in Human Behavior	72	Novak, et al. [113]	Marketing Science
35	Card et al.[114]	Ergonomics	73	Annett [115]	Occupational Psychology
36	McFarlane et al.[16]	Human-Computer Interaction	74	Nielsen et al.[116]	Proceedings of the SIGCHI
37	Kieras and Meyer [117]	Human-Computer Interaction	75	Ekman [118]	Psychological Bulletin
38	Webster and Martocchio [119]	MIS Quarterly			

IJHCS = International Journal of Human-Computer Studies;

PAMI, IEEE = Pattern Analysis and Machine Intelligence, IEEE Transaction on

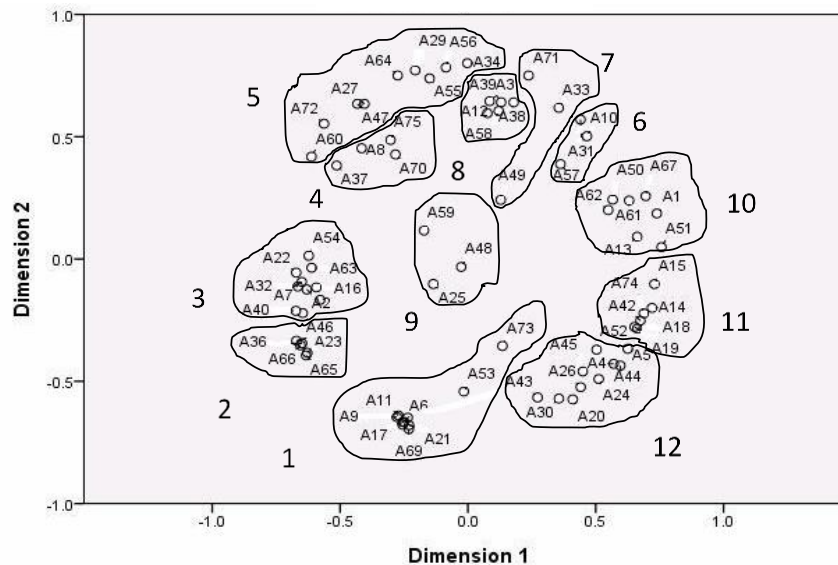


**Figure 1 Cluster analysis**



## 4.2 Analysis

In order to graphically identify the group of HCI, hierarchical cluster analysis with Ward's method and multidimensional scaling (MDS) were applied to these 75 representative highly cited articles. The results were analyzed into dendrograms and MDS are shown in Figure 1 and Figure 2. In Figure 2, the horizontal axis (dimension 1) represents the type of subject, from system (left) to human (right). On the other hand, the vertical axis (dimension 2) indicates the type of operation, including implementation (bottom) and evaluation (top).



**Figure 2 Multidimensional scaling**

For hierarchical cluster analysis methods, the rate change in the similarity measure as clusters combine, it indicates the number of clusters. We can classify the results into twelve clusters and apply the classification result of cluster analysis for a comparison with the points grouped in MDS. This shows that two classification results are quite similar except four articles ([53], [114], [100], [105]) were not present in the MDS groups and two articles ([72], [74]) were not in the same groups.

Based on the Pearson's correlation matrix, the factor analysis was conducted by applying SPSS statistical software. The principle component analysis was implement with a varimax rotation to extract the maximum number of possible documents with the minimum number of conceptual factors in HCI. The results revealed fifteen factors. These representative articles are shown in Table 2. One document (73. Annett [114]) was dropped due to a factor loading of less than 0.5. These factors explained (SPVE) 85.6 percent of the variance.

**Table 2. The factors in HCI developed by factor analysis**

Factor	Highly cited articles (No.)	Eigen	PVE	SPVE
1	7,2,32,16,22,63,41,54,40,35	8.94	11.92	11.92
2	21,6,9,17,11,28,68,69,53	8.09	10.79	22.71
3	18,74,19,42,14,15,5,51	6.03	8.04	30.75
4	65,46,66,36,23	5.31	7.09	37.83
5	3,12,38,39,58	5.05	6.73	44.56
6	30,20,43,26,44	4.72	6.30	50.86
7	1,61,13,62,50,67	4.51	6.01	56.86
8	55,56,29,34,64	3.97	5.30	62.16
9	45,4,24,52	3.07	4.09	66.25
10	27,47,72	3.02	4.03	70.28
11	10,57,31,	2.76	3.68	73.96

Factor	Highly cited articles (No.)	Eigen	PVE	SPVE
12	25,48,59	2.59	3.46	77.41
13	33,49,71	2.13	2.84	80.25
14	70,75	2.09	2.79	83.03
15	37,8,60	1.95	2.60	85.64

Note: PVE = Percent of variance explained; SPVE = Sum of Percent of variance explained

Moreover, comparing the classification of cluster analysis with the result of factor analysis (Table 3), it can be seen that most of the groups are identical, and only four clusters were combined from two or three partial groups, such as cluster 4 that combined the results of factor 14 and part of factor 15, and cluster 11 contained some of the papers in the factor 3. This result indicates that the discovered research streams from different analysis methods are quite consistent with each other. Therefore, the classification results of cluster analysis are selected. The naming of each conceptual themes and the contents are discussed in the following paragraphs.

**Table 3. Comparison between cluster analysis and factor analysis**

Cluster	Factor	Conceptual theme	Cluster	Factor	Conceptual theme
1	2	System capability	7	13	Interface analysis
2	4	User interface design	8	5	Performance measurement and improvement
3	1	Task of the HCI system	9	12	Development of interaction
4	14, partial 15	Evaluation of interaction	10	7	Human reaction to technology
5	8, 10, partial 15	User acceptance of technology	11	Partial 3	Facial expression
6	11	Personalized system design	12	Partial 3, 6, 9	Effective interaction

### 4.3 The core knowledge of HCI

#### 1. System Capability

The key concern of the HCI is the ability of the system. The studies in this group focused on the capability, the elements, and functions of HCI systems. Weiser [67] predicted the specific elements and ability of computers for the 21st century. Scheirer, et al. [87] developed a slow interface to frustrate users, to collect users' physical and behavior data, and then provided the recommendations and guidelines for HCI measurement. Research [57] and [63] indicated that users may reflexively apply social rules and expectation to computers. Based on cognitive psychology, Kieras and Polson [100] concluded that when the user's knowledge is adequately simplified, a system can be made to be more usable. Venkatesh, et al. [79] reviewed several IT acceptance modules and formulated a unified one. Hornbæk [107] reviewed the current practice and research in measuring usability in HCI, and compared subjective and objective measures of usability.

#### 2. User Interface Design

This group contains the framework of interface design and influential factors. Vicente and Rasmussen [101] proposed a theoretical framework, ecological interface design (EID), for designing interfaces for complex HCI systems. Three prescriptive design principles were suggested. Starner, et al. [99] presented two systems designed for recognizing American sign language (ASL). McFarlane and Latorella [16] identified automated monitoring and interruption as an important issue for HCI, and suggested an approach of user-interface design to help people effectively manage the interception. Venkatesh and Davis [91] developed an extended model of TAM (Technology Acceptance Model), TAM2, and showed that the social influence processes and cognitive instrumental processes significantly influenced user acceptance. Ghani and Deshpande [62] described the task characteristic and use experience of optimal flow theory in HCI.

#### 3. Task of the HCI System

These studies highlight different types, novel and traditional types, of task related to HCI system. Yang, et al. [77] surveyed the techniques developed to detect faces in an image. Hoffman and Novak [89] introduced a structural model of user navigation behavior in a hypermedia computer-mediated environment. Sproull, et al. [95] discovered that user interaction with a talking-face interface was different than with a text-display interface. Users may change their response behavior when computer interface become more “human-like”. Johnson, et al. [78] investigated the new learning environment of an animated teaching agent, a lifelike character with the capability of face-to-face learning interaction. Payne and Green [51] developed a formal model of the mental representation of task language. Klein, et al. [108] designed HCI systems to actively support users to manage and recover from negative emotional states. Card, et al. [114] evaluated four different interactive devices about reaction time and error rate. Soukoreff and MacKenzie [53] made several recommendations to HCI researchers for the evaluation of pointing devices. Davis [50] and Davis, et al. [59] evaluated and compared different models in terms of the level of the users’ IT acceptance.

#### **4. *Evaluation of Interaction***

Studies in this group focused on the evaluation of interface expression methods. Polson, et al. [109] presented a methodology for evaluations of user interface designs early in the design cycle. Ekman [118] concluded that facial expression is universally applied, no matter in literate or preliterate cultures. Kieras and Meyer [117] described the EPIC (Executive Process-Interactive Control) cognitive architecture for modeling human multi-task performance. Miller [61] showed the amount of information that the user received or processed for the unaided observer is severely limited; he further used various techniques to break the information bottleneck.

#### **5. *User Acceptance of IT***

Technology acceptance is an important issue for an HCI system. This group discusses the related topics about users’ technology acceptance. Nass, et al. [98] showed that users applied social rules to respond to computers, and they responded to techniques that were inconsistent with their beliefs. Sundar and Nass [90] provided the evidence that people responded to computers as an independent source of information. Webster, et al. [112] defined the playfulness in HCI in terms of flow theory, and the dimensionality of the flow construct. Agarwal and Karahanna [64] found that the users’ characteristics of playfulness and involvement were important factors for cognitive absorption and concern for the usage of IT. Lavie and Tractinsky [80] found that the visual aesthetics of computer interfaces are important factors of a users’ satisfaction. Tractinsky, et al. [102] analyzed the degree to which a system’s aesthetics affected the perceptions of both its aesthetics and usability. Davis [82] applied TAM to describe why a user accepts or rejects IT, and how this affects system design features.

#### **6. *Personalized System Design***

Most of the studies in this group were concerned about the personalization concepts for users for the HCI system design. The studies in this group were relatively recent, all being conducted after 1995. Nass, et al. [65] claimed that computers could have personality like humans, and people preferred to work with a computer with a similar personality to their own. Venkatesh [106] demonstrated that the perceived ease of use was an important factor influencing user acceptance and usage behavior of information technologies over time. Fischer [120] addressed user modeling in that the design of a human-computer system should be carried out as if it works for individual. This makes the system more usable, useful, and learnable.

#### **7. *Interface Analysis***

This group contains different technologies of interface analysis. John and Kieras [66] compared four different GOMS (Goals, Operators, Methods, and Selection rules) models of user interface analysis techniques. Larkin and Simon [110] pointed out that the diagrammatic representation is better than the sentential one for the interface. And movement control, which may apply in the interface design, was evaluated in Fitts and Peterson [111]. This topic is a mature issue, with all of the studies being published before 1996.

## **8. Performance Measurement and Improvement**

One of the main purposes of HCI research is to increase the interaction performance. Therefore, the research in this group highlights the measurement of technology performance and improvement. Fitts [52] tested and provided support for the Fitts model. MacKenzie [69] provided a theoretical context for the Fitts model, and thereby refined it. Cohen, et al. [49] tested different classifiers and developed a new architecture for automatically segmenting and recognizing human facial expression from video sequences. Webster and Martocchio [119] indicated that when measuring implications for the workplace, researchers should focus more attention on the positive influence on HCI, rather than on the negative ones.

## **9. Development of Interaction**

There are many types of interactions between humans and computers. The studies in this group focused on recognizing different interactive situations and provided various interactive development guidelines. Picard, et al. [94] developed the machine's ability and emotional intelligence to recognize human affective states. John and Kieras [66] provided guidance about different GOMS to be used for different HCI design situations. Trevino and Webster [88] concluded that the type of technology, perceived technology characteristics, and organizational factors positively influence user evaluations and perceived impacts.

## **10. Human Reaction to Technology**

The studies in this group focused on the technique models related to HCI, and the user's reaction reflected techniques in the design and implementation stage. Pavlovic, et al. [18] surveyed the visual interpretation techniques of hand gestures for HCI. Rabiner [71] reviewed the theoretical statistical methods in speech recognition. Taylor and Todd [103] compared three models which could help to understand the usage of IT, and the factors that influence systems use through the application of both design and implementation. Dowell and Long [92] presented a conception that expressed the general design problem more formally and that was embedded in engineering principles.

## **11. Facial Expression**

Considering the interaction between humans and computers, facial expression is probably the easiest way to express human intentions. Research in this group has examined different aspects during the reorganization and expression process. Moon and Nass [75] found that computer personalities are psychologically real to users. Essa and Pentland [73] described a computer vision system to observe facial motion. Picard and Klein [55] provided a theoretical and practical implication of interactive computer systems to detect and label human emotional expression. Pantic and Rothkrantz [81] surveyed the capability of the human visual system and provided a guide for the development of an automatic facial expression analyzer. Fasel and Luettin [83] reviewed the most prominent automatic facial expression analysis methods and applications in the area of HCI, and discussed the classification of these methods.

## **12. Effective Interaction**

Studies in this group focus on two themes. The first centers on the future development, whereas the second describes the technologies related to the user's behavior and affective states. Hudlicka [96] introduced the available methods and technologies of affective HCI. Fogg and Nass [85] observed that the flattery from a computer can produce the same general effects as that from humans. Pantic and Rothkrantz [56] provided a set of recommendations for developing an affective intelligent multimodal HCI. Abowd and Mynatt [104] reviewed a new paradigm of interaction, ubiquitous computing. This paradigm marks a fundamental change in the relationship between humans and computers. Murray and Arnott [21] discussed human vocal emotion and related principal findings. Russell [60] suggested that a model of affection, rather than being independent, has affective dimensions that are interrelated in a

highly systematic fashion and fall in a circle. Cowie, et al. [54] developed a hybrid system that can use information from faces and voices to recognize people's emotions. Gray, et al. [93] validated the accuracy of GOMS predictions and how the models can be used to guide the design before they are implemented.

The emerging intellectual structure of HCI appears when comparing the results of multidimensional scaling and hierarchical cluster analysis. The result of the analysis is shown in Figure 1, in which three class can be seen. The first class, named system development, contains three major themes: (1) System capability, (2) User interface design, and (3) Task of the HCI system. The second class is called interaction usage and covers six major themes: (4) *Evaluation of interaction*, (5) *User acceptance of IT*, (6) *Personalized system design*, (7) *Interface analysis*, (8) *Performance measurement and improvement*, and (9) *Development of interaction*. This class is related to the implementation stage and technologies in the interaction. The third class, impact of interaction, includes three major themes: (10) *Human reaction to technology*, (11) *Facial expression*, and (12) *Effective interaction*. Research in this class investigated the impact of the interaction as it relates to the influence of HCI, especially the user's response to the system.

#### 4.4 Discussion and Comparison

The highly-cited papers in the twelve clusters are expressed using the published year, and illustrated in Figure 3. The size of the point represents the amount of the papers in certain year.

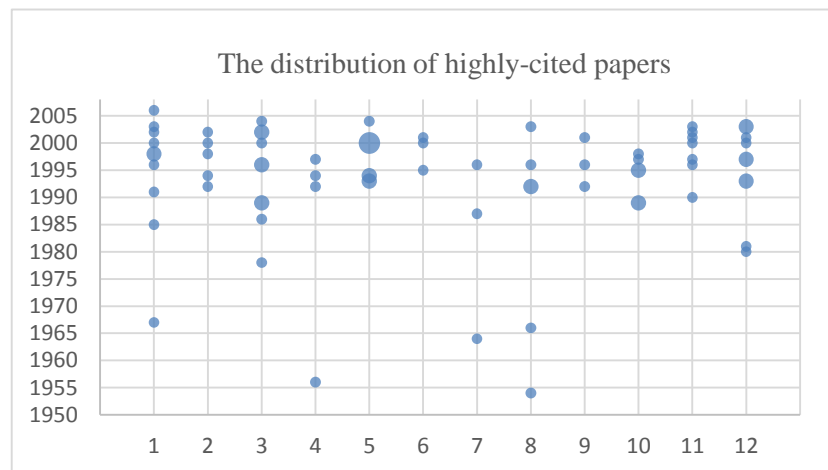


Figure 3. The distribution of highly-cited papers from twelve clusters.

From this figure, although there are time delays due to limitation of the co-citation mechanism, some patterns can still be found. First, there are some papers which were cited much earlier than the 1970s [52, 61, 111]. They may either be the reference disciplines which heavily influence the development of HCI, or they are the main thread of the HCI sub-filed in the early development, such as Miller [61], which contributed the HCI field by examining the user's capability of processing information, and Fitts Law [52, 111] was one of the main research threads of the HCI field in the early stages. Secondly, in the highly-cited papers, the clusters of 4, 7, 10 (Evaluation of Interaction, Evaluation of Interaction, Human Reaction to Technology) are associated with the 1990s, but they do not have follow-up papers after the year 2000. This situation may indicate that these clusters did not attract much research attention afterword, and they do not seem to currently fall into the main stream. Clusters 1, 3, 12 and 5 contain more papers than the others, and with the first three extending over a long period of time, it seems that these clusters have continuously received much attention; as for the articles of cluster 5, they are concentrated during a certain period, indicating a research interest explosion during that time. All of these suggest that they are still main stream trends in the HCI field.

#### Category level Comparison

The comparison focused on 2 levels: category level, and topic level. The topics derived from this

research were compared to the related research of HCI in the past. The categories of textbooks and the article of Zhang, et al. [9] were selected. There have been several popular HCI textbooks [121-123] in the academic field, each of them having its specific perspective. Most of these categorized the HCI field by subject, with the main categories being *Human*, *System*, *Interaction Design*, and *Implementation*. And for Zhang, et al. [9], these three top-level categories reflect IT artifact lifecycle stages, which they called “*IT development*” and “*IT use and impact*” and “*General research*”.

When comparing these three classification perspectives at the category level, a certain similarity was found. The first class of this research, *System development*, is similar to the *IT development* category of Zhang’s research, and the category of “*System*” in the textbooks. They are all related to the development stage of the system. For the second and third class of our research—“*Interaction usage*” and “*Impact of interaction*”—they match the category of IT Use and Impact of Zhang’s research, and the category of “*Interaction design*” and “*Implementation*” in the textbooks. They are all concerned with the implementation and impact of HCI. The similarity of these categories confirms that the research method of this research is on the right track.

**Table 4 categories comparison**

Zhang, et al. [9]		This research	
Category	%(/824)	Category	%(/75)
<b>A. IT development</b>	<b>12.0%</b>	<b>A. System development</b>	<b>28.0%</b>
A1 Development methods and tools	0.7%	(1) System capability	10.7%
A2 User analyst involvement	2.1%	(2) User interface design	6.7%
A3 Software/hardware development	2.2%	(3) Task of the HCI system	10.7%
A4 Software/hardware evaluation	0.4%		
A5 User interface design & development	3.0%	<b>B. Interaction usage</b>	<b>36.0%</b>
A6 User interface evaluation	2.8%	(4) Evaluation of interaction	5.3%
A7 User training	0.8%	(5) User acceptance of IT	12.0%
<b>B. IT use and impact</b>	<b>83.3%</b>	(6) Personalized system design	4.0%
B1 Cognitive belief and behavior	26.1%	(7) Interface analysis	4.0%
B2 Attitude	15.2%	(8) Performance measurement and improvement	6.7%
B3 Learning	3.5%	(9) Development of interaction	4.0%
B4 Motivation #	8.2%		
B5 Emotion	3.9%	<b>C. Impact of interaction</b>	<b>30.7%</b>
B6 Performance	14.8%	(10) Human reaction to technology	9.3%
B7 Trust	6.1%	(11) Facial expression	9.3%
B8 Ethics	0.6%	(12) Effective interaction	12.0%
B9 Interpersonal relationship	4.1%		
B10 User support	0.7%		
B11 Other #	0.1%		
<b>C. Generic research topics</b>	<b>4.6%</b>		
C1 Research #	4.2%		
C2 Education #	0.4%		

# do not exist in Zhang and Li [2]

### Topic level Comparison

While comparing the topics of different researches, a number of differences became apparent. Basically, the classification of the textbooks and Zhang’s paper derive from a similar perspective based on the subject of HCI, and this perspective may explain the hierarchical structure of discipline. The topics derived by Zhang, et al. [9] was based on this framework, which is a broad HCI framework. However, a potential drawback is that although there is a subject list in the framework, it may receive little attention from the researcher, and thus prevent these topics from becoming intellectual core research topics. From Table 4, it can be seen that although there are about 20 topics in Zhang’s research, many of them account for less than 1% of the total articles (A4, A7, B8, B11, C2). This situation indicates that the topic list cannot fully represent the research interest or intellectual core topics. The method of decomposing a framework may not be suitable to explain the intellectual core of this discipline. In this research, the topics were explored according to a data-driven co-citation approach, with each topic having a certain factor loading that can represent the intellectual core and research interest. The rating of this research in the right column of Table 4 supports the research method.

Reviewing the content of the clusters/topics in this research, some of them can be mapped to one

or two research topics of Zhang's research, such as (2) *User interface design* correlating with (A5) *user interface design and development*, (4) *Evaluation of interaction matching*, (A6) *user interface evaluation*, and so on. Those mapping clusters clearly affirm the key trends of HCI. However, some of the topics in Zhang's research, such as *Learning*, *Trust*, *Ethics*, and *Interpersonal relationship*, do not appear at all in the core knowledge of this research. The possible reason is these topics have not yet received enough attention.

Moreover, the clusters (6) *Personalized system design* and (11) *Facial expression* do not correlate with any similar topics in Zhang's research. This suggests that these two topics could be a new intellectual core (research interest) that did not attract much attention at the beginning of the 2000's. Jain and Li [124] developed automatic recognition and analysis of human face and facial expression. Fasel and Luettn [82] observed that automatic facial expression analysis has become an active research area. And the sub-field of personalized design has already become a well-accepted concept in HCI, such as information dissemination [125], search engines [126], medicine [127] and especially E-commerce [128]. These studies highlight the application of personalization technology and their commercial potential [129].

## 5. CONCLUSION

The purpose of this research was to explore the intellectual core and main trends of HCI. Seventy-five of the most frequently cited papers in the field of HCI were collected and analyzed. Citation and co-citation were used to discover the underlying core intelligence of HCI, and the methods of factor analysis, multidimensional scaling, and cluster analysis were applied. Given that these methods all obtained similar results, the classification of the cluster analysis were selected to explain the core knowledge of HCI. The twelve following core groups of HCI were identified: *System capability*, *User interface design*, *Task of the HCI system*, *Evaluation of interaction*, *User acceptance of technology*, *Personalized system design*, *Interface analysis*, *Performance measurement and improvement*, *Development of interaction*, *Human reaction to technology*, *Facial expression*, and *Effective interaction*. *System capability* was found to be the key factor concerning the capability and elements that the present and future HCI system should have. Considering the interactive system, the architecture of *User interface design* could be the main concern, especially for complex HCI interface. The *Task of the HCI system*, such as detecting faces in an image, modeled navigation behavior and managed user emotion. *Evaluation of interaction* focused on the evaluation methods of interactive technologies. *User acceptance of technology* discussed the factors of user acceptance, with TAM being one of the main theories discussed in this group. From *Personalized system design*, users seem to prefer interacting with a system with a similar personality; therefore, the interactive system should be designed in order to serve the individual. The studies in this group are relatively recent and published after 1995. *Interface analysis* focused on the technologies of interface design, with studies including the comparison of different user interface analysis technology models, presentation methods and movement control methods. This topic is a mature issue with all studies being published before 1996. *Performance measurement and improvement* discussed the performance model of human reaction, and the performance improvement technologies of HCI. *Development of interaction* focused on the development of providing a guideline for different design situations, recognizing human affective states, and investigating the influence of different factors. *Human reaction to technology* discussed many technique models related to HCI, and the user's reaction were reflected in the technologies in the design and implementation stages. *Facial expression*, in the context of HCI, is probably the easiest way to express human intentions; studies in this group examined different considerations during the reorganization and expression process. Finally, *Effective interaction* looked to the future development of interaction and the technologies related to the user's behavior and affective states.

The above twelve groups could be merged into three *categories* to express the trends of HCI fields. The first trend is *System development*. This relates to the development of the HCI system, including the capability of HCI system, the architecture of interface design, and the task related to the HCI system. Studies here mainly focused on the pre-implementation stage of the HCI system. The second trend is *Interaction usage*. This cluster is related to the implementation of the interaction system, including interaction design, presentation, control, measurement and improvement. The third trend is the *Impact of interaction* and focused on the influence of HCI, especially the user's response to the system.

The result of the twelve clusters were spread out and compared with relevant research. In the distribution of the clusters, very few highly-cited papers were published before the 1970s early development of the HCI field, such as Miller [61] on the user capability of processing information, and the application of Fitts Law [52, 111] in interface design. Moreover, from the time distribution of each cluster, the clusters 4, 7, 10 (Evaluation of Interaction, Evaluation of Interaction, Human Reaction to Technology) did not have any highly-cited papers after the year 2000, which may indicate that while they were intellectual trends, they did not attract as much attention as in the past. On the other hand, the clusters 1, 3, 5, 12 represent the main current intellectual core according to their distribution of papers.

This study's findings were compared with those of related research to evaluate their similarities as well as the shift in core knowledge. One of the most related studies, Zhang, et al. [9], was selected for evaluation. In the top (categories) level, there were certain similarities at the top level frameworks from different methods or perspectives, and no serious conflict exists. However, comparing the topics of different researches, a number of differences were found. In this research, 2 new clusters (6) *Personalized system design* and (11) *Facial expression*, were explored, but these did not appear in Zhang's topic list. They seem to represent the new intellectual cores which did not attract much attention in the past, and these topics can be clearly recognized nowadays. Facial expression is probably the easiest way to express human intentions and has become an active area of research. As for personalized design, it has already become a well-accepted concept in HCI. Moreover, observing each topic, some new research issues have been established based on mature ones, such as measuring usability in the cluster of system capability, detecting faces in images and animation in the cluster relating to HCI tasks, and playfulness in user IT acceptance.

In summary, this research enhanced the understanding of the core knowledge in the HCI field, explored the novel research topics in the on-going shifting intellectual structure, and found new issues in different existing topics. Researchers may gain a more complete picture of the HCI field of study, explore the novel topics and new research issues, and research title and methods in each topic. This research may help researchers to extend the research area, develop new or extended methods based on the new IT environment, especially for new technologies, such as mobile, ubiquitous, and wearable devices. For practitioners, this research provides an intellectual core and indicates the key topics and trends. In addition, during the stages of the commercial design and development of new systems for various devices, project managers can pay more attention to the information the core topics provided in this study at either the design, implementation or evaluation stages.

There are two limitations in this research that should be addressed. Firstly, the research data in this study were collected from the ISI web of knowledge. Most of the important journals were collected for this study, but a few important journals were not, such as "Cyberpsychology, Behavior, and Social Networking" and "ACM Transactions on Accessible Computing". Therefore, in the future research, other journal databases can be considered for inclusion. Secondly, the method applied in this research, the co-citation method, has a time lag limitation. Important and newly published papers can only be included when enough papers cite them, and it normally takes quite a long time to reach this threshold. Thus, the future study of exploring the core knowledge of HCI needs to pay special attention to these newly published papers in the journals discussed in this research.

#### **Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

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