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# Understanding the formation of interdisciplinary research from the perspective of keyword evolution: a case study on joint attention

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**Abstract**
Understanding the formation of interdisciplinary research (IDF) is critically important for the promotion of interdisciplinary development. In this paper, we adopt extracted keywords to investigate the features of interdisciplinarity development, as well as the distinct roles that different participating domains play in various periods, and detect potential barriers among domains. We take *joint attention* (JA) as the study domain, since it has undergone a development process from a topic of one domain to interdisciplinary research (IDR). Our empirical study has yielded interesting findings. First, we detect the phenomenon of knowledge diffusion as it evolved through three domains of JA. It enabled us to observe the shift of roles the domains played during the process of IDF, as well as the existence of potential barriers among these domains. Second, according to the diffusion and development process of JA among domains, three phases that an IDR field in general goes through were identified: a latent phase, an embryo phase, and a mature phase. Third, domains may play different roles in distinct periods, with the formation of IDR. Four roles are identified: knowledge origin, knowledge receiver, knowledge respondent, and interdisciplinary participant. This paper showcases how to detect the evolution of IDR by analyzing keyword evolution. By giving the profiles of IDR fields and descriptions of keyword evolution, it would be valuable for policy makers and regulators to promote IDR development.

**Keywords** Interdisciplinary formation · Joint attention · Keyword evolution · Interdisciplinary communication

**Mathematics Subject Classification** 94A05

**JEL Classification** D83

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## Introduction

Innovation and creative thinking are key factors driving scientific breakthroughs, and often come from one domain creating or influencing another. For instance, nature has stimulated many technological advances throughout history, such as bird flight inspiring the design of fixed-wing aircraft. Interdisciplinary research (IDR) has thus become not only beneficial but also necessary for successful invention and transformation in a range of fields, notably when tackling complicated scientific problems in health and medicine, natural sciences, and social sciences. The concept of interdisciplinarity has been discussed by many researchers (Huutoniemi et al. 2010; Rosenfield 1992). In this paper, we adopt the term "interdisciplinarity" as a mode of research that integrates concepts or theories, tools or techniques, information or data from different bodies (domains) of knowledge (Porter et al. 2006).

The question of interdisciplinary scholarly communication (Bracken and Oughton 2006; Schaltegger et al. 2013) and interdisciplinary evolution (Chang, and Huang 2012; Pan et al. 2012) has been widely researched in the past years. However, there are few studies offering a clear understanding of the formation process of interdisciplinary research from its beginning. Understanding interdisciplinary formation (IDF) from the perspective of keyword evolution is the focus of this paper. First, it helps us learn the particular development features of interdisciplinarity that reflects a possible timeline of IDF process. According to our analyses, the Joint attention (JA) field, a typical interdisciplinary case, generally undergoes three major phases—a latent phase, an embryo phase, and a mature phase during the IDF process. In the latent phase, JA is inactive and confined to a single domain; in the embryo phase, interdisciplinarity is slowly forming, which reveals unidirectional knowledge diffusion between domains; in the mature phase, the IDR shows an obvious growth in domains' involvement, and becomes an integrated field featured with multidirectional knowledge diffusion among domains. Second, we identify distinct roles different participating domains played in various periods: A knowledge origin is a domain from which original knowledge emerged; a knowledge receiver is a domain to which knowledge diffused from other domain(s) to solve problems by their own; a knowledge respondent defines a domain that once was a pure knowledge receiver but now shift its role to a knowledge exporter; and an interdisciplinary participant defines a domain that participates in the integration of multi-domain knowledge after IDR formed. Third, it is beneficial to detect potential barriers among disciplines, especially identical terms within similar research context used in two disciplines at a particular period with different indications, and thus help researchers tackle these disciplinary obstacles.

Joint attention (JA) is selected for the case study in the current paper. It has been defined as visually coordinating attention to an event or object with another individual, sharing interest, and social engagement, and showing an understanding that the partner is sharing the same focus (Mundy and Stella 2000). JA has be researched in multiple domains,[1] yet some of them (e.g., linguistics, psychiatry, education, and neurosciences) purely applied JA-related theories and have fewer interactions with other domains. However, three domains, namely child psychology (CP), robotics, and human–computer interaction (HCI), have deeply focused on JA for years and have obvious interaction effects on JA research development along with each other; they are therefore suitable for us to illustrate the process of IDF.

[1] "Domain" in this paper means a field of study that defines a set of common requirements, terminology, and functionality to solve a problem in a given field.

Methodologically, previous studies have provided several feasible ways to analyze interdisciplinarity evolution, such as topic modeling (Chen et al. 2017; Xu et al. 2015), coauthorship network analysis (Newman 2004; Zhang et al. 2018), and (co-)citation analysis (Hemmarfelt 2011). While a research topic can be regarded as a cluster of keywords (Griffiths and Steyvers 2004), authors' topics are often represented as accumulated topics of their publications (Rosen-Zvi et al. 2004). Meanwhile, citation relationships can be regarded as impact relations existing between topics (He et al. 2009). Neither research topics nor citation relationships is the best choice to indicate information exchange between domains from a fine-grained level. In this study, therefore, we adopt keywords to analyze knowledge diffusion between domains as well as the formation of interdisciplinary. The reason lines in two aspects. On the one hand, as the minimum knowledge unit, keywords represent the specific concepts in a direct and clear way. On the other hand, keywords are more valid and timely to track the knowledge communication among domains, since, for instance, the same keyword used in different domains and/or periods may well indicate the knowledge it carries and how it diffuses. Hence, keywords are used in this study to trace the concrete knowledge diffuse in a fine-grained level, and thereby to reveal the features of interdisciplinary field formation and potential barriers among domains. Specifically, we investigate the keyword and co-occurring keyword evolution of JA research to reveal the process of IDF from the latent to the mature phase. In particular, our research objective is to understand how JA, a matured interdisciplinary field, evolved from one single domain to an interdisciplinary domain. In this process, we are interested in how different domains play their distinct roles in forming this interdisciplinary field dynamically. To achieve this, we analyze how keywords of publications in JA changed and how they co-occurred.

This paper is organized as follows. We first discuss the studies related to our study, giving attention to the formation of interdisciplinarity, keyword evolution, and JA. We then detail the data and methods for our analyses. Next, we present our findings and their interpretations. Finally, we conclude with a summary of our findings, their limitations, implications, and final thoughts for future research.

## Related studies

### Research question perspective: the formation of interdisciplinarity

Although the evolution of IDR has been investigated (Vangrunderbeek et al. 2013; Chang and Huang 2012; Pan et al. 2012; Gingras and Larivière 2010), little attention has been paid to the formation process of interdisciplinarity, as well as its features in different development phases. From the perspective of teamwork organization in IDR, Klein (1990) proposed a life cycle of IDR that includes three phases: a planning phase, in which resources such as time, seed money, space, and common facilities are established, and release time and rewards negotiated; an implementation phase, in which effective management and improving connections among participating disciplines are essential; and a concluding phase, in which mission-directed measures of success, such as reciprocal learning, group problem-solving, and implementation of results in a social/technological context rather than an academic context can be applied for evaluating the process of IDR. Chakraborty (2018) explored the "trajectory of life" of the Data Mining domain, using citation analysis, and revealed that a field in general goes through three phases – a growing phase, in which the field accumulates ideas from other fields; a mature phase, in which the field produces many in-house citations; and an interdisciplinary phase, in which the field receives many citations from other fields.

Neither the life cycle of Klein nor the life trajectory of Chakraborty reveals the interdisciplinary process from its origin to mature interdisciplinarity, from the perspective of research content evolution, nor the roles played by participant domains and their unfolding. Hence, the purpose of the present study is to investigate the IDF process by using keyword analysis in the field of JA.

## Methodology perspective: keyword evolution

Although keyword analysis has several unavoidable drawbacks, such as depending on the scope of the dataset (Law et al. 1988) and assuming that different keywords have non-trivial relations between their referents (Whittaker 1989), it was regarded as a quantitative (Callon et al. 1986) and flexible (He 1999) way to trace the diffusion and paths of knowledge, since keywords are well-representative for articles' ideas and topics (Griffiths and Steyvers 2004).

Studies focusing on using keywords to understand the evolution of a certain domain include those of Ord, Martins, Thakur, Mane, and Börner (2005), who examined the keywords and titles of publications in the field of animal behavior, and evaluated their similarities as a way to understand the field's development. Yoon and Park (2005) employed factor analysis for exploring keyword evolution, to show technology developments and opportunities. Huang (2009) revealed the trend of specialization in the obstructive sleep apnea domain and told of finding a lack of continuity in this field with keyword-level analyses. By analyzing keyword evolution in Management Information Systems (MIS), Choi, Yi, and Lee (2011) detected several clusters for keywords in different periods of time, and argued that interdisciplinary keywords have potential to lead future MIS research. Additionally, many have made contributions to discovering topical leads and lags across corpora from the perspective of keyword evolution.

Our study differs from previous studies in three aspects. First, we aim to research on knowledge diffusion between domains by tracing the diffusion of concrete concepts (represented by keywords) that reveal the features of IDF process. Second, we combine the analysis based on phases divided by approximately equivalent periods and the analysis based on phases divided by interaction features among domains, which provides a more comprehensive view to understand the formation of interdisciplinarity. Third, three domains and four time spans are identified in this study for revealing the process of IDF in a fine-grained level.

## Case field perspective: joint attention

As summarized by Schertz (2005), joint attention (JA) is defined as visually coordinating attention to an event or object with another individual, sharing interest and social engagement, and showing an understanding that the partner is sharing the same focus (Mundy and Stella 2000; Schertz and Odom 2004; Tomasello 1995). The ability to share attention with an adult involving a third object or actor is a very important step in children's language development (Kwisthout et al. 2008). Developmentally, Mundy et al. (2007) observed that infants displayed a wide range of meaningful individual differences in JA development from the first through the second year of life.

Extending from JA-related studies in the CP field, research centering on the same topic is also found in the fields of robotics and HCI. Kozima (2001) highlighted the necessity of a JA ability for social communication between a human and a robot. In a recent study, Yu et al. (2010) also stressed that JA has been recognized as a critical component in human–robot interactions. Horvitz et al. (2003) pointed out that humans have a limited spotlight of attention and this constraint on attentional resources makes communication among people rely deeply on attentional signals. This fact has significant implications for how computational systems and interfaces are designed. Imai et al. (2001) devised a JA mechanism for a robot and evaluated its validity through a psychological experiment. The result indicated that eye-contact and attention expression were significant factors in joint attention.

By gleaning through JA-related studies in the domains of CP, robotics and HCI, it is clear that JA, as a topic of inquiry interest, has undergone the whole development process, from a single-domain topic to an interdisciplinary field, and has been widely interwoven among these three research domains. Taking JA as the study case in this study enables to reveal a typical IDF process.

## Methodology

### Data

Previous studies related to JA are widely spread in various domains, especially in CP, robotics, and HCI; hence, we cannot simply limit our data source to any specific domain journals or databases. Instead, we adopt Google Scholar as our data source, for it has the broadest coverage for scientific publications, and its search results provides rich information for each record, including publication year, title, Uniform Resource Locator (URL), document type, author, venue, publisher, abstract, and the number of citations received; these are helpful for analyzing interdisciplinary evolution among domains related to JA.

With the help of domain experts, we carefully design five search terms: “joint attention child,” “joint attention robot,” “joint attention HCI,” “joint attention robot child,” and “joint attention interaction.” We limit the study to articles published in 1970–2014, since the origin of JA research dates back to 1970s (Moore and Dunham 2014). In this way, we obtain 100,926 articles. Since Google Scholar limits search results to the first 1000 from each search query, we confine each search queries by publication year, to obtain as many search results as possible. Considering there is a limited number of articles before 1985, we set 15 years for the first time span and 10 years for those following, so that the first span has sufficient records and we are therefore able to proceed comparable keyword analyses among different time spans. Therefore, the time spans are 1970–1984, 1985–1994, 1995–2004, and 2005–2014. However, we find that some records are not related to JA—for example, those that include “joint” but not “attention”. Hence, we remove articles not containing “joint attention” and other related terms[2] in their title and abstract.

To better understand the dynamic IDF process between different domains, the records are further divided based on the corresponding terms: “child” for CP, “robot” for robotics, and “HCI”, “human computer interaction”, or “human–computer interaction” for the HCI domain. If an article contains more than one term listed above, it is counted in distinct domains multiple times. Duplicate records are also removed if they have the same title, publication year, and first author. Thus, we have 5940, 1690, and 137 articles for these

[2] Related terms include “shared attention,” “shared focus,” “shared gaze,” “eye gazing,” “dyadic attention,” and “triadic attention.”

three domains, respectively. Table 1 shows some descriptive statistics on the number of articles about the three domains in four different time spans.

### Keyword extraction

The C-value algorithm (Frantzi et al. 2000) is employed to extract keywords from the titles and abstracts of the articles, and to assign a score to each.

Since many of the extracted keywords are segmented with errors[3] or meaningless phrases,[4] we need to manually process and remove those incomplete and non-related keywords before the co-occurrence analysis. In addition, keywords like "autism spectrum", "autistic spectrum", and "spectrum disorder" need to be merged since they have similar meaning. Therefore, we take three steps to obtain the keywords that were used for co-occurrence analysis. First, we collect top-scored 500 keywords of each domain as our candidate keyword set since higher C-Value means higher quality of extracted keywords (Frantzi et al. 2000). Second, we manually remove meaningless or fragmentary keywords from the set, and merged similar keywords, such as: (1) "autism spectrum disorder," "autism spectrum," and "autistic spectrum"; (2) "children with autism" and "children with ASD[5]"; (3) "eye gaze" and"eye gazing"; and (4) "human–robot interaction," "human–robot interaction," and "robot–human interaction." Third, keywords frequency are counted to identify more meaningful keywords in co-occurrence analysis. Figure 1 shows the cumulative distribution of keyword frequency in the three domains, where the horizontal axes represent the logarithmic keyword frequency plus one. As we can see, top 20% keywords in each domain have obviously higher frequencies than others. Since high-frequency keywords are more meaningful and representative in the domains, we leave top 20% keywords of each domain for the co-occurrence analysis.

Finally, a total of 113 keywords are included after these procedures, and they constitute our final keyword list.[6] Table 2 shows the most frequently used 20 keywords in our list.

### Co-occurrence analysis

Co-occurrence is defined here as two keywords occurring in either the title or abstract of the same article. Based on keywords co-occurring with "joint attention," we consult domain experts, and carefully select two additional keywords, "autism spectrum disorder" and "humanoid robot," as representative keywords in the JA field as well as "joint attention" itself. We construct a co-occurrence matrix for "joint attention," "autism spectrum disorder," and "humanoid robot," and visualize the results temporally, so as to detect the evolution of the co-occurring keywords.

[3] For example, in some records crawled from Google, the keyword "robot control" may be wrongly expressed as "robot contr ol", and therefore cannot be extracted correctly.

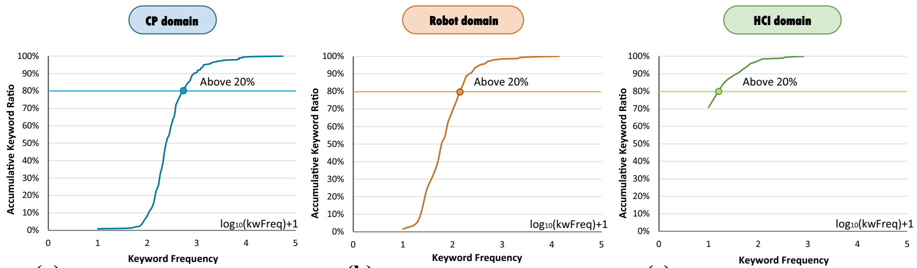
[4] For example, the extracted keywords "et al." and "first year" are meaningless and therefore need to be removed manually.

[5] ASD = autism spectrum disorder.

[6] The keyword list for our analysis can be visited at: https://figshare.com/s/101bea52d494c211f221.

**Table 1** Number of records in the three domains in four time spans

| Domain | 1970–1984 | 1985–1994 | 1995–2004 | 2005–2014 | Total |
|---|---|---|---|---|---|
| CP | 115 | 471 | 1676 | 3678 | 5940 |
| Robotics | 1 | 4 | 233 | 1452 | 1690 |
| HCI | 0 | 3 | 26 | 108 | 137 |
| Total | 116 | 478 | 1935 | 5238 | 7767 |




**(a)** Keyword frequency distribution in CP domain **(b)** Keyword frequency distribution in Robotics domain **(c)** Keyword frequency distribution in HCI domain

**Fig. 1** Distribution of keyword frequency in three domains

**Table 2** The 20 most frequently used keywords in our word list

| id | Keyword | Frequency | id | Keyword | Frequency |
|---|---|---|---|---|---|
| 1 | Joint attention | 6946 | 11 | Theory of mind | 260 |
| 2 | Children with autism | 1859 | 12 | Attention skill | 207 |
| 3 | Shared attention | 1354 | 13 | Language development | 206 |
| 4 | Autism spectrum disorder | 862 | 14 | Social cognition | 202 |
| 5 | Young child | 853 | 15 | Shared focus | 180 |
| 6 | Social interaction | 426 | 16 | Social skill | 172 |
| 7 | Autistic child | 412 | 17 | Eye gaze | 166 |
| 8 | Human–robot interaction | 322 | 18 | Attention mechanism | 165 |
| 9 | Humanoid robot | 304 | 19 | Attention behavior | 151 |
| 10 | Eye contact | 291 | 20 | Language acquisition | 151 |

## Results and analyses

### Overview of JA-related studies

Figure 2 shows changes in the number of publications among the three domains in the JA field, where the blue, red, and green lines represent CP, robotics, and HCI domains, respectively.

Figure 2 shows that the development of JA field can be roughly split into three periods: 1971–1983, 1984–2002, and 2003–2014, according to their interdisciplinary evolution

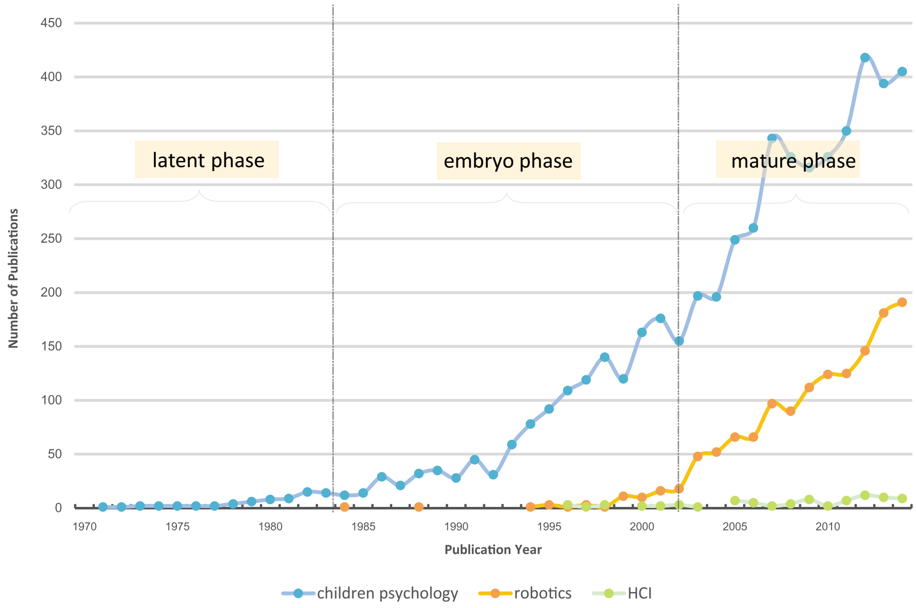



**Fig. 2** Number of JA publications over time

features from a disciplinary background to an interdisciplinary one. In the first period (1971–1983), JA-related research originated from CP since its first publication published in 1971. From then on, JA has displayed a long period of development only in the CP domain, until the year 1984, when the first JA publication appeared in the robotics domain. Since no other domain displayed JA research publications in this period, we call this period the *latent phase* of IDF.

The second period (1984–2002) witnessed the diffusion of JA knowledge from the CP to the robotics domain, and then to the HCI domain. In this period, JA research publications in the CP domain obviously increased. Meanwhile, JA-related studies gained attentions from the robotics domain, and then HCI, although the number of publications grew slowly. Nevertheless, interdisciplinarity was slowly forming among the three domains, and featured with unidirectional knowledge diffusion between different domains that is confirmed in section “Formation Process of JA Interdisciplinary Research”. We call this period the *embryo phase* of IDF.

In the third period (2003–2014), the number of publications in the CP domain continued growing. Meanwhile, JA-related research publications grew in the robotics domain, and slightly increased in HCI. Furthermore, in section “Formation Process of JA Interdisciplinary Research” we confirmed that IDR became an integrated field in this phase, and it is hard to tell which study comes from any single domain, due to the multidirectional knowledge diffusion among domains. We therefore call this period the *mature phase* of IDF.

To analyze the research content evolution from the keyword aspect through all the periods, we select the top five keywords adopted in JA-related studies every two years, after we integrate keywords with similar meanings (e.g., “children with autism,” “autism spectrum,” and “autism spectrum disorder” are all represented by “children with autism,” “joint attention,” “shared attention,” “visual attention,” “shared focus,” and “focus of attention" are all represented by "joint attention", etc.), and label them on line chart of publication quantities in Fig. 3.

Figure 3 shows that JA research showed an accelerating development trend after the latent phase of IDF. We also find that keywords have different occurrence patterns in each period. First, there were some keywords consistently occurring in every period, such as "children with autism," indicating that autism was a focus of JA over a long period. Second, some keywords occurred in certain period(s), and might disappear later, while others appeared only in later period(s). For instance, "language acquisition" occurred in 1975–1976, but disappeared in 1979–1980 and 1987–1988. Other language-related keywords, such as "language development" (occurred in 1979–1980 and disappeared in 2001–2002) and "early language" (occurred in 1981–1981 and disappeared in 1997–1998), also show the "appear-disappear" pattern. On the other hand, keywords like "social interaction" and "eye contact" have continuously occurred in the list since 1987–1988 and 2001–2002 respectively. This indicates that JA was researched from a language development aspect at its initial phase, and then research focus shifted to other topics with time (Mundy et al. 1990; Tomasello 1995). Last but not least, robot-related keywords like "humanoid robot," "human–robot interaction," and "human–robot" appeared on the list since 1999–2000, which is in the embryo phase of IDF. This shows that although JA originated in the CP domain, research increased when other domains became involved. This elicited an interest in JA as an example of interdisciplinarity.

## Formation process of JA interdisciplinary research

As proposed by Stirling (2007), the concept of diversity comprises three different factors (attributes): (1) variety: the number of distinctive categories; (2) balance: evenness of the distribution of categories; and (3) disparity or similarity: degree to which the categories are different/similar. In this section, we focus on the dynamic evolving of keywords in interdisciplinary participant domains on the bases of the property "variety" (different numbers of active domains participating in interdisciplinary research in different phases) and "balance" (different roles with varying degrees of importance that domains played in different phases) of diversity. Diversity measures (Leydesdorff 2018; Porter and Rafols 2009; Rafols and Meyer 2010; Zhang et al. 2016) can be used to evaluate the degree of

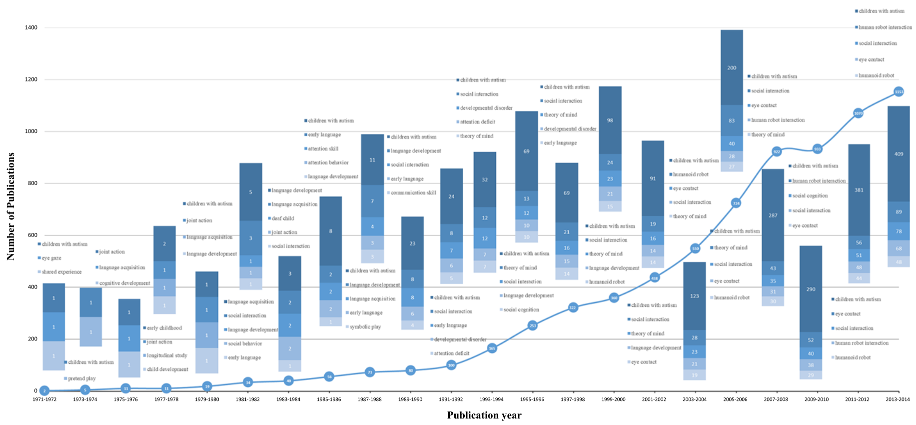



**Fig. 3** Top five keywords in the JA field over time

interdisciplinarity. However, to better reveal the concrete knowledge diffusion and their impact on the formation process of interdisciplinary research, we take the distribution of keywords as our method of analysis, instead of diversity calculation.

By tracking keyword evolution and overlap among domains through 4 periods—1970–1984, 1985–1994, 1995–2004, and 2005–2014—we can follow the formation process of JA interdisciplinary research in different phases. In addition, since the concepts of three phases (latent, embryo, and mature phases) of IDF mentioned above are divided from the perspective of intrinsic development features of IDR, they are adopted to help explain the features of IDF for each period that divided purely by the equal time span in a more comprehensive way.

As shown in Figs. 4, 5, 6 and 7, three big circles serve as different domains, colored with blue, light pink, and green; small circles, like tiny pie charts, represent different keywords, and their sizes show their frequencies. The area of intersection between circles illustrates the extent of interdisciplinarity of these keywords.

In 1970–1984 (Fig. 4), most keywords occurred in the CP domain, but the size of the small circles representing keywords was small, indicating that the frequencies of the keywords were low. Moreover, only one keyword, "joint attention," which is found overwhelmingly found in the CP domain (the ratio between the CP domain and robotics is 85:1), occurs in the intersection of CP and robotics in this period. Nevertheless, no keyword was found to occur in other domains.

Based on this observation and related studies (Liem 1974; Norden 1981; Walberg and Marjoribanks 1976), we can conclude that in the first period (1970–1984), JA studies focused on specialized problems such as education of young children, family environment, and cognitive development, which happened in the inner domain of CP. There was almost no JA research in either robotics or HCI. This means that JA did not belong to interdisciplinary research in that period and was undergoing the latent phase of IDF.

In 1985–1994 (Fig. 5), although keyword frequencies in the CP domain were apparently higher than those in the other two domains, the number and frequency of keywords that

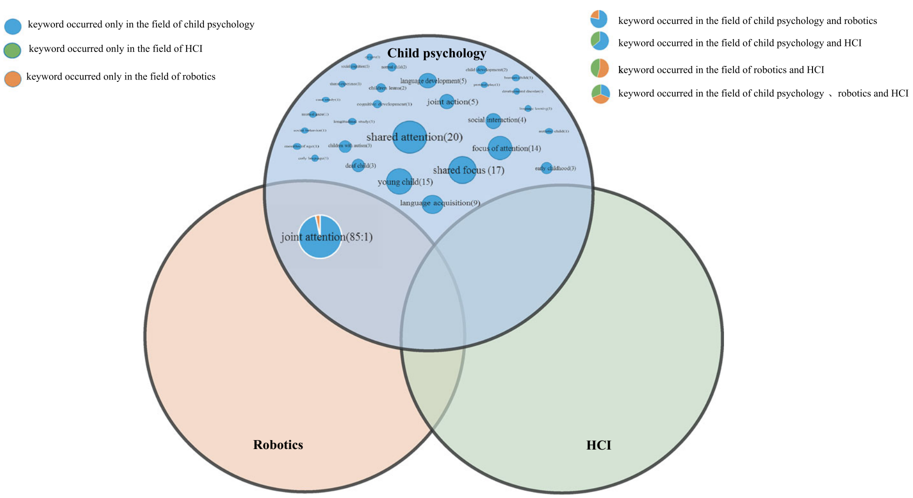



**Fig. 4** Interdisciplinary trend of keywords (1970–1984) (the ratios, such as $a$:$b$:$c$, that appears beside the pie-chart captions, shows the percentage of certain keywords occurring in the domains of CP, robotics, and HCI)

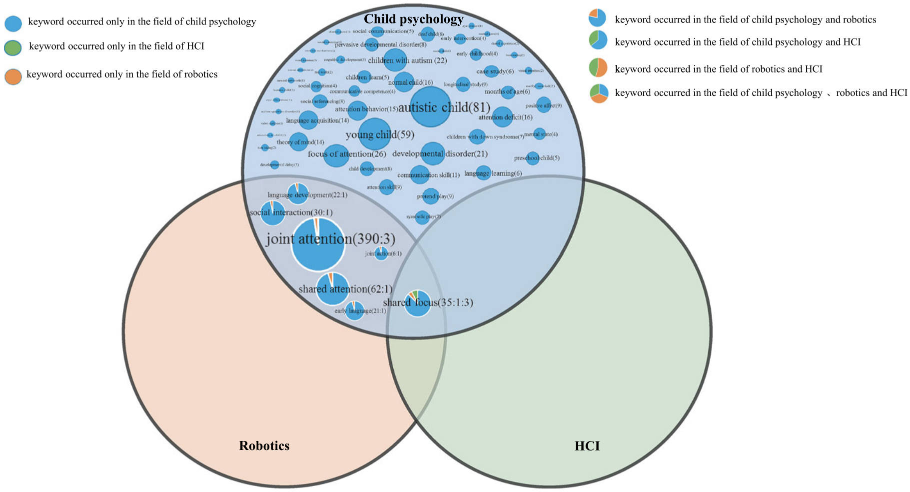



Fig. 5 Interdisciplinary trend of keywords (1985–1994)

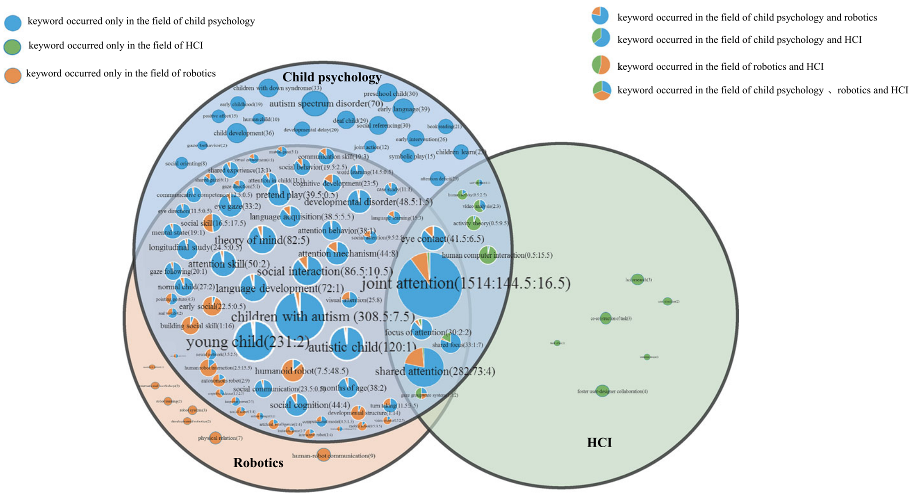



Fig. 6 Interdisciplinary trend of keywords (1995–2004)

occurred in robotics had significantly increased. This means that JA knowledge, once studied solely in the CP domain, began diffusing from CP to robotics. All the keywords in robotics appeared in the intersection between CP and robotics, revealing that JA knowledge was applied in robotics to improve the adaptability of robotics systems (Goldenberg and Chan 1988). Moreover, the keyword "shared focus" appeared in the intersection of the three domains, indicates that the HCI domain was involved in JA researches into designing collaborative task environments (Hefley and Romo 1994; Young and Abowd 1994).

In the second period, interdisciplinary JA research was going through the embryo phase, which featured unidirectional knowledge diffusion from CP to robotics and HCI. The degree of interdisciplinary research among the three domains was not intensive, since most JA knowledge was occurring in robotics and HCI, to solve their special problems, and little

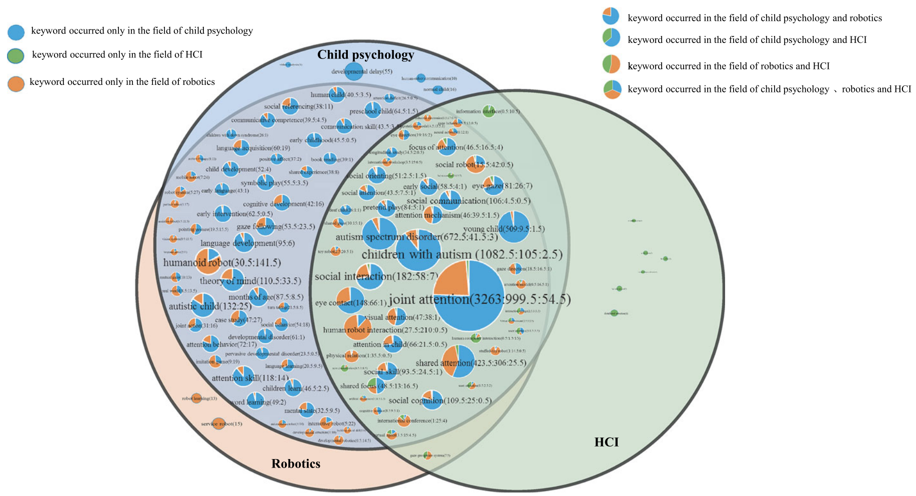



**Fig. 7** Interdisciplinary trend of keywords (2005–2014)

research collaboration happened between domains. JA interdisciplinary research was still developing, or possibly undergoing a multidisciplinary phase, since knowledge from different domains may be mutual and cumulative without being integrative (Klein 1990).

In 1995–2004 (Fig. 6), the number of keywords that once appeared only in the CP domain decreased greatly; those only in robotics increased, though their frequency was low; and the HCI domain showed only its unique keywords. As for intersecting areas, the CP and robotics domains began to share more keywords that had belonged only to CP in the preceding periods; this could be the reason that the number of keywords in CP decreased. Another source of the increasing number of keywords in the intersection of CP and robotics came from previous robotics domains. Thus, two potential keyword evolution paths are summarized: (a) from CP to robotics (e.g., "children with autism," "young children," and "social cognition"), and (b) from robotics to CP (e.g., "mobile robot," "social robot," and "human–robot interaction"). Similarly, we can detect two paths between the CP and HCI domains: (c) from CP to HCI (e.g., "video analysis") and (d) from HCI to CP (e.g., "human computer interaction" and "user interface"). These paths reveal the latent keyword evolution flows among domains in distinct periods over time. Moreover, the three domains shared many keywords that had migrated from CP, and most of them have similar meanings to "joint attention."

Based on the keyword distribution in and among domains, we make two observations. First, keywords that belong to the robotics domain and the HCI domain separately increased significantly, which indicate that JA knowledge was no longer provided only by the CP domain (Nagai et al. 2002; Raeithel and Velichkovsky 1995). Second, robotics—once the only JA knowledge importer—turned into a "reverse knowledge feeder." For example, Hideki and Akira (1998) developed a robot that can follow people's attentional targets, to study infant language acquisition. Dautenhahn and Billard (2002) used a small humanoid robotic doll in autism therapy. Since knowledge integration between domains had begun to happen in this period, we labeled this period as an early phase of "mature."

Unlike Fig. 6, Fig. 7 (2005–2014) shows additional integrative trends of the three domains: CP, robotics, and HCI had fewer keywords unique to the respective domains; the number and frequency of the keywords shared by CP and robotics increased; all three domains shared more keywords, with higher frequencies. All these trends indicate that the involvement level of each domain was higher than before. JA research is becoming integrated; it is hard to tell which study may have come from any single domain. For example, Bekele, Lahiri, Davidson, Warren, and Sarkar (2011) developed a novel adaptive and individualized robot-mediated system for joint attention, to provide intervention services for children with autism. It is a representative study that applies robotics knowledge to solve typical problems in CP. Mobahi and Karahalios (2005) proposed that HCI shows promise for aiding children with mental disorders because it provides the possibility of capturing, analyzing, and influencing human perception and behavior, which is another interdisciplinary study that integrates knowledge from HCI and CP. Hence, JA interdisciplinary research has reached the mature phase.

When revisiting the four periods, we find that JA is a representative case that demonstrates all three phases of IDF: latent, embryo, and mature. We characterize them as follows: In the latent phase, a field is inactive and confined to a single domain. The field does not formally belong to interdisciplinary research since no other domain joins in. However, the fundamental research seeds the future IDR. In the embryo phase, interdisciplinarity is slowly forming, with unidirectional knowledge diffusion between different domains, although the degree of IDR involvement of new joined domains is not intensive. Direct knowledge flow between domains and little inter-domain research collaboration happens. In the mature phase, IDR increases in domains, and become an integrated field, such that it is hard to tell which study comes from any single domain, due to multidirectional knowledge diffusion among domains. Furthermore, the phenomenon that keywords were grouped in the CP domain, and only later in robotics and HCI, shows a latent evolution path for keywords—from traditional and theoretical to emerging and applied domains. The fact that some keywords had occurred in CP very early but only occurred in robotics and HCI after many years also indicates the existence of potential barriers among these domains.

## Role shift of JA participant domains

While keywords can be used to analyze the core concepts of different domains in every period, the co-occurring keywords of important keywords, which directly connect concepts behind keywords (Su and Lee 2010), can be used to depict the context of a target keyword, as well as its evolution over time. To explore the shift in roles that domains played in the JA field, we extract the keywords co-occurring with “joint attention” in the three domains separately, and show them in Figs. 8, 9 and 10. Two years are set as the analytic window in our analyses.

### CP domain

From the perspective of the CP domain (Fig. 8), we can see that “joint attention” displayed obvious increases in the number and frequency of co-occurring keywords by the 1980s. When it comes to research interests in different periods in the CP domain, two features can be concluded. First, co-occurring keywords like “language development” and “language acquisition,” followed by “young child”, “autistic child”, etc., frequently occurred before 1990s but seldom witness after that, indicating that the language acquisition problem of young child or autistic child has been one of the major focused JA related researches. Second, top co-occurring keywords with “joint attention” in 1987–1994 and 1995–2014

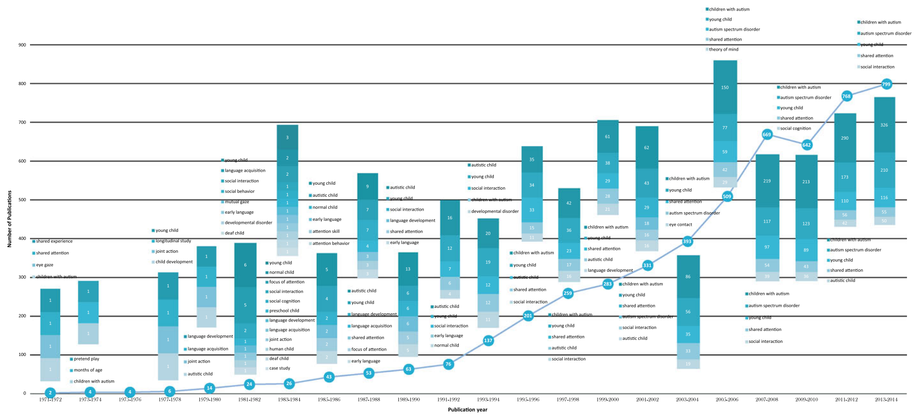



**Fig. 8** Change in the numbers of publications and co-occurring keywords of "joint attention" in CP (Top five most frequently co-occurring keywords as well as their frequency are noted in each period of the domain)

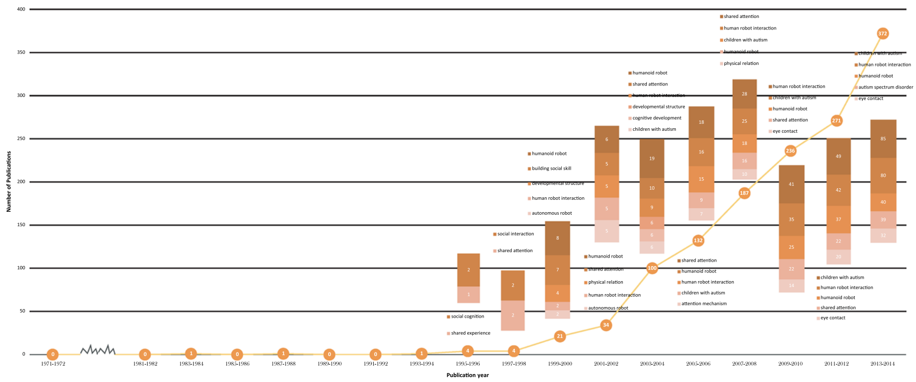



**Fig. 9** Growth in number of publications and co-occurring keywords of "joint attention" in robotics (Top five most-frequently co-occurring keywords and their frequencies are marked for each period of the domain)

were "autistic child" and "children with autism", which have similar meanings. They indicate that the research topic of pursuing the therapy for autism in CP is always the focus of JA throughout all periods. It also confirms the occurrence of "people-first language" (PFL) recommended by advocacy groups (Blaska 1993), who aim to prevent subconscious dehumanization by naming the persons first and then the condition (Fox 2011). By preventing adjectives before nouns, the PFL type of English, many researchers started to adopt the keyword "children with autism" to represent "autistic child."

As noted in earlier sections, the CP domain is the origin of JA-related research studies, and focuses attention on JA throughout. We can barely find any co-occurring keyword from the top-five most frequently co-occurring keywords (including tie) that has typical characters of robotics and HCI domains. It means the main focus of JA-related research in the CP domain has a significant research route.

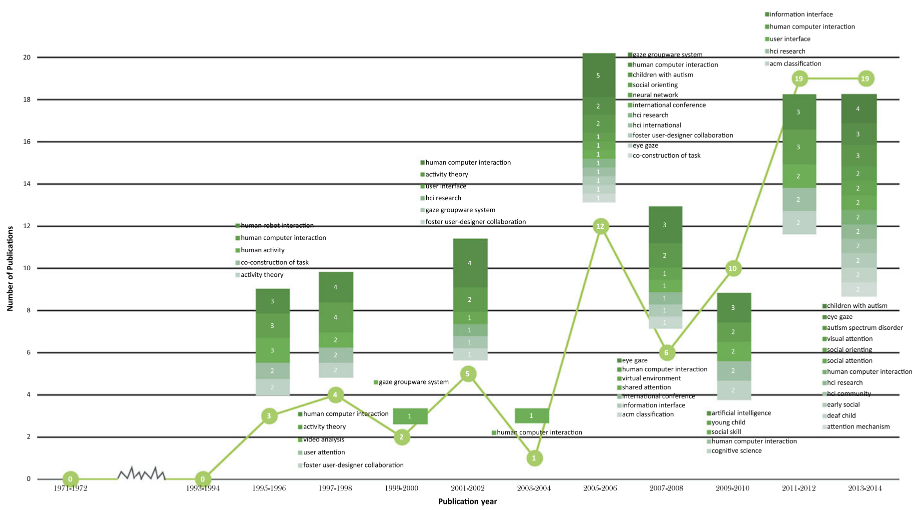



**Fig. 10** Dynamic change in number of publications and co-occurring keywords for “joint attention” in HCI (The top five most-frequently co-occurring keywords their frequencies are noted for each period of the domain)

## Robotics domain

Figure 9 shows that the number of publications and co-occurring keywords of JA are very low until the year 1995–1996. Then they significantly accelerate after the year 2001–2002, indicating that the number and depth of the studies focusing on JA increased. From the distribution of co-occurring keywords, we see that JA research content went through three noticeable periods. In the early age of JA research (1995–1998), researchers focused on theoretical study of constructing social interactions and shared attention mechanisms with robots (Scassellati 1996). In the second period (1999–2004), the high-frequency co-occurring keywords “humanoid robot” and “humanoid robot interaction” indicate that the topic of developing humanoid robots with interactive ability became a research hotspot (Kanda et al. 2004). Until then, the co-occurrening keywords of “joint attention” in the robotics domain were quite different from those in CP, which reflects the distinct context of the JA research in the two domains. However, “children with autism” and “autistic child” first co-occurred with JA in the domain of robotics, indicating a tendency to link robotics and child autism studies (Duquette et al. 2008). The third period (2005–2014) featured co-occurring keywords “humanoid robot” and “children with autism,” which indicates a trend of using humanoid robots in adjuvant therapy for children with autism (Robins et al. 2005; Huang and Thomaz 2010).

Unlike the CP domain, the robotics domain plays the role of a typical knowledge receiver, which applies theories from the CP domain to address the interaction problems of humanoid robots. However, with the success of JA research in the robotics domain, knowledge originating in this domain also applies to problems of the CP domain, which indicate that the robotics domain gradually changed from being a pure knowledge receiver to becoming a knowledge respondent, and integration with other domains has significantly increased.

### HCI domain

Figure 10 shows the dynamic change in numbers of publications and co-occurring keywords of JA in the HCI domain. The year 1996 witnessed the first three publications related to JA. Within 1995–2004, there were several co-occurring keywords, such as "human–robot interaction," "human–computer interaction," and "human activity," but we failed to detect stable concentrated co-occurring keywords. This illustrates that JA research in HCI domain had not fallen into a fixed pattern in these periods. From 2005 to 2006, there were significantly increasing keywords, such as "social orienting" and "eye gaze," co-occurring with JA. Another point of interest is that "children with autism" first began to co-occur with JA, indicating the starting point of autism research in this domain. Subsequently, the increasing frequency of keyword "children with autism" and the similar keyword "autism spectrum disorder" shows researchers' continuing interest in autism from the HCI perspective.

Figure 10 also shows that the HCI domain has acted as a knowledge receiver from the outset, since JA co-occurring keywords like "activity theory" and "user attention" typically came from the CP domain. However, the increasing frequency of co-occurring keyword "children with autism" in later periods indicates that HCI knowledge was applied to CP problems, which means the degree of interdisciplinary integration has increased, and that the HCI domain acts as both knowledge respondent and participant.

According to the above analysis, we conclude that domains may play different roles in different periods during the IDF process Specifically, four roles are identified: "Knowledge originator" describes domains that generate original knowledge and act as knowledge exporters; a "knowledge receiver" applies knowledge diffused from other domains to problems in its own domain; a "knowledge respondent" imports and applies knowledge from other domains in early stages, but influences other domains through knowledge export in later stages; an "interdisciplinary participant" is a domain that joins the integration process of multi-domain knowledge after an IDR is fully formed.

### Co-occurring keywords evolution for typical keywords in JA

To demonstrate interactional effects among domains while the interdisciplinary research of JA is developing, we selected two keywords, "autism spectrum disorder" (ASD) and "humanoid robot" (HR), to trace the development and co-occurrence with the keyword list generated in the section "Keyword Extraction". The reason we select them is that they are representative terms originated separately in CP and robotics, and have obvious impacts on other domains along with the development of JA. The co-occurring keywords analysis of typical keywords in their original domain as well as in other domains further demonstrates the interactional effects among domains as the interdisciplinary JA research is developing.

### Co-occurring keywords evolution of ASD

The co-occurring keywords evolution of ASD is shown in Fig. 11. The number of papers referring to ASD in the CP domain increased rapidly after 1997. Its most important co-occurring keywords were "joint attention" and "children with autism," which are representative keywords of the CP domain. It means the ASD research studies in the CP domain have their own development path.

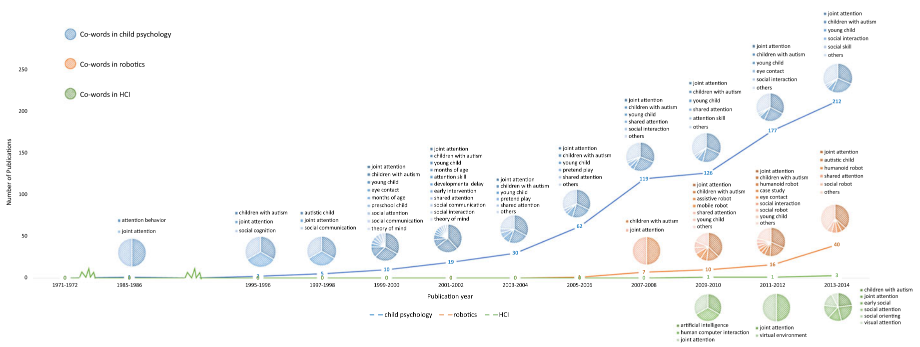



**Fig. 11** Changes in number of publications and co-occurring keywords of "autism spectrum disorder" (Blue, orange, and green lines represent CP, robotics, and HCI, respectively. Numbers on the lines are paper counts. The top-five most-frequently co-occurring keywords as well as their share of the total co-occurring keywords, are noted as pie charts for each period). (Color figure online)

As for the robotics domain in Fig. 11, the number of papers referring to ASD increased after 2007, which was 10 years after their first appearance in the CP domain, although the number of such papers was not a large share of CP domain papers. The delay in their appearance indicates the direction of knowledge diffusion, from CP to robotics. Furthermore, the initial research period of ASD in robotics was characterized by the co-occurring keyword "children with autism," a typical CP keyword. This obvious lead-lag phenomenon confirms the earlier observation of the relation between the knowledge origin role played by the CP domain and the knowledge receiver role played by the robotics domain. However, other co-occuring keywords began to appear in the robotics domain in later periods besides common co-occurring keywords, such as "children with autism," "shared attention," and "eye contact." For example, "mobile robot," "humanoid robot," and "social robot," which appeared after 2009, are typical keywords from robotics. This phenomenon indicates that knowledge diffusion is no longer unidirectional in the later periods, and the robotics domain shone more light on ASD in its role of knowledge respondent and interdisciplinary participant. It also approximately corresponds to the mature phase of interdisciplinarity formation, which further confirms the reasonableness of the phase division.

With respect to the HCI domain in Fig. 11, a paper containing "ASD" and "joint attention" first came out in 2010, with the co-occurring keywords "joint attention,""artificial intelligence," and "human–computer interaction" in Guldberg, Porayska-Pomsta, Good, and Keay-Bright (2010). It described how experts from different domains work together to create a multimodal environment related to JA and shared understanding for children, and summarized the challenges faced by researchers in the HCI domain. The paper count increased slowly in 2009–2014, yet co-occurring keywords such as "artificial intelligence" and "virtual environment" indicate that HCI tries to play the roles of knowledge respondent and interdisciplinary participant, by integrating HCI domain knowledge to help solve ASD problems.

## Co-occurring keywords evolution of HR

When analyzing the trend of numbers of publications related to HR and "joint attention" in CP (Fig. 12), we find that it starts small and grows slowly as time goes by. Compared to the

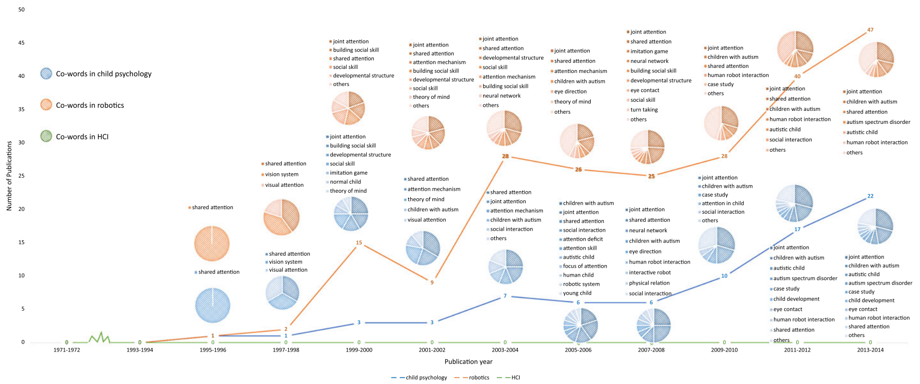


**Fig. 12** Changes in number of publications and co-occurring keywords of "humanoid robot" (Blue, orange, and green lines represent CP, robotics, and HCI, respectively. Numbers on the lines are paper counts. The top-five most-frequently co-occurring keywords, as well as their share of total co-occurring keywords, are noted as pie charts for each period). (Color figure online)

CP domain, the robotics domain grows more quickly. There is no related research in the HCI domain during any period.

By comparing to the co-occurring keywords of HR in CP domain and robotics domain (Fig. 12), we find that they present different patterns from that seen in Fig. 11. The two domains are consistent in terms of co-occurring keywords (such as "shared attention," "eye contact," and "human–robot interaction") from starting point to the last period. Furthermore, although some co-occurring keywords (such as "theory of mind" and "children with autism") appeared earlier in the CP domain, they appeared in robotics lists soon thereafter. Similarly, co-occurring keywords (such as "neural network") that appeared earlier in the robotics domain also appeared in CP domain lists soon thereafter. The ASD research in two domains, as one domain (CP) plays the role of knowledge origin and deeply influences the development of ASD research in other domains (robotics and HCI), the consistency of co-occurring keywords indicates that the CP and robotics domains are highly integrated as interdisciplinary participants in research related to HR and JA, which further confirms the previous mature phase designation (2003–2014) of interdisciplinarity that the major development periods of HR evince.

## Discussion and conclusions

This paper explores IDF from the perspective of keyword evolution, and adopts JA as a case study. It is critically important for the promotion of interdisciplinary development, by investigating the development features of interdisciplinarity, as well as the distinct roles that different participant domains played in various periods, and detecting potential barriers among domains. There are three aspects we want to highlight in this paper. First, a keyword-based longitudinal analysis is applied to track the concrete concept during knowledge diffusion between domains, therefore revealing the formation process of interdisciplinary field from a fine-grained level. Second, during the analysis based on phases divided by approximately equivalent periods (four time spans: 1970–1984, 1985–1994, 1995–2004, and 2005–2014), the interdisciplinary evolution phases (three phases: latent, embryo, and mature phases) are also taken into considerations and provide a more comprehensive way to understand the features of different phases. Third, we apply keyword analyses in a complex, dynamic background composed of multiple domains and time spans (three domains and four time spans in this study), which gives us an ideal situation to understand how concrete concepts have been diffused and/or interacted among domains.

The results of our empirical study show many interesting findings:

First, we detect the phenomena of knowledge diffusion and evolution among three domains, which also share some research topics. For instance, two topics, ASD and children with autism, are both focused upon by researchers in the three domains. From a temporal perspective, the evolution of keywords illustrates a flow pattern—from CP to robotics, and then to HCI in the former periods, which indicates knowledge diffusion from traditional and theoretical to emerging and applied areas. However, the knowledge flow does not correlate with the increase in JA research. The increasing frequency of keywords originating from robotics and HCI shows they underwent a shift from pure knowledge receivers to knowledge respondents and participants, and the integration among domains has significantly increased. Meanwhile, the fact that some keywords occurred in CP very early, but occurred in robotics and HCI after many years indicates the existence of potential barriers among these domains.

Next, the JA case study presents a landscape of the formation process shown by IDR, which generally undergoes three major phases – a latent phase, an embryo phase, and a mature phase. In the latent phase, a field is inactive and confined to a single domain. The field does not formally belong to IDR since no other domains are involved. Nevertheless, the fundamental research seeds the future IDR. In the embryo phase, interdisciplinarity is slowly forming, which reveals unidirectional knowledge diffusion between domains—although the degree of IDR of newly joined domains is not intensive. Direct knowledge flow between domains and research collaboration happens infrequently between domains. In the mature phase, the IDR shows obvious growth in domains' involvement, and becomes an integrated field so that it is hard to tell which study comes from any single domain, which multidirectional knowledge diffusion among domains.

Last but not least, domains may play different roles in distinct periods in the formation of IDR, according to the keyword evolution analysis of JA. Four roles are identified: knowledge origin, knowledge receiver, knowledge respondent, and interdisciplinary participant. Knowledge origin and knowledge receiver are opposite concepts; the former defines the domain from which original knowledge emerged, and the latter defines the domain to which knowledge diffused from other domain(s) to solve problems in their own. A knowledge respondent defines a domain that once was a pure knowledge receiver shift its role to that of knowledge exporter. And interdisciplinary participant defines the domain that participates in the integration of multi-domain knowledge after IDR has formally formed.

These findings have several implications. Methodologically, this paper showcases how to detect the evolution of IDR by analyzing the keyword evolution, which could be common to multiple domains when applied. From the JA perspective, this study provides a birds'-eye-view for domain researchers, not only because it presents JA development within long periods, but also shows the temporal change from three different domains, which breaks with the convention that researchers in these domains share little with each other, including methods, objects, perspectives, and frameworks. As for IDF, our findings reveal the diffusion and development process of JA among three domains, showing that an IDR field in general goes through three phases: a latent phase, an embryo phase, and a mature phase, and the four roles domains played during the IDF: knowledge origin, knowledge receiver, knowledge respondent, and interdisciplinary participant. By giving the profiles of IDR fields and a keyword-evolution description, one can build up an evaluation model based on the IDF process, to determine the degree of IDR development. It would be valuable for scientific policy makers and regulators to use it as a reference to promote IDR development.

The current paper has several limitations. First of all, the formation process model presented in this paper may not be universally accepted, and therefore requires a more thorough understanding of the keyword evolution of fields from other domains. Nevertheless, we believe that the present observation can motivate researchers from other domains to explore the IDF paradigm in particular areas, and thus be a reasonable future directions to study. Second, the process that interdisciplinary fields develop into disciplines (van den Besselaar and Heimeriks 2001) is untouched in this study due to the limitation of JA field. Third, this study only focused on the three domains that have clear JA research development trajectory and obvious interaction effects on JA research development, but do not take into consideration other domains related to JA. In the future, we will study on the overview of JA research and its applications on all related domains.

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