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What Do We Really Talk About When We Talk About Context in Pervasive Computing: A Review and Exploratory Analysis

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ABSTRACT

At the heart of ubiquitous and pervasive computing is the integration of semantically rich contextual information into systems that intelligently adapt their behavior to the context. This paper presents an analysis of the contextual elements considered in the scientific discourse on pervasive computing. To support researchers with positioning their work, this paper explores how well the facets of context are represented and which context elements are particularly important in specific application domains, such as healthcare or traffic. Results suggest that context elements are considered diversely among domains. Context spreads across a long tail of heterogeneous, rather specific context elements. Potential factors explaining this high diversity relate to sensor technology, structure of context information as well as purposes and design of context-aware systems.

1 INTRODUCTION

Over the last decade, there has been a trend towards increasingly sophisticated systems which are aware of the context that they are used in, and intelligently adapt their behavior to this context [4]. These systems approach Weiser's vision of intelligent environments, where technology is ubiquitous, pervading everyday life, but disappears into the background Weiser [28]. Based upon Weiser's vision, the community works towards the seamless integration of information and services into real-life, everyday systems [4]. While the community refers to these intelligent system environments with different names, such as "context-aware", "adaptive", "situated", "ambient", etc., we hereafter refer to them as "context-aware systems". The major research fields, researching, designing, and investigating such context-aware systems are "pervasive computing" or "ubiquitous computing".

The pivotal element of context-aware systems is 'context'. There is an ongoing debate on what constitutes context. Definitions of context vary by knowledge domain; but convergence seems to exist about context being helpful in the process of constructing a representation about an object and acting "like a set of constraints that influence the behavior of a system (a user or a computer) embedded in a given task" [7]. The literature presents many different attempts to divide context into different categories and subcategories; such categorizations and models range from ones that state a few context categories on a rather high level of abstraction (e.g., [23]) to ones that enumerate a broad scale of context elements as subcategories (e.g., [20]) [23]. The widely cited definition by Dey and Abowd [15] goes even further and defines context as "any information that can be used to characterize the situation of an entity" (p. 3). In other words, the conceptualizations of context range from 'any kind of information' to only a few categories. It is emphasized in the body of work (e.g., [23]) that context may not be looked at from a purely generic perspective, as there are domain-specific aspects that have to be considered. To date,

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though, literature does not present any work that discusses the various facets of context that are to be considered domain-specific.

Filling this research gap, this paper presents an analysis on the contextual dimensions that the community considers in its research practice on pervasive computing. We particularly focus on domains-specific aspects, analyzing which context elements are discussed in which application domains. Our analysis sheds light on how context is understood by the community. The systematic representation of our analysis' results provides a structure that helps researchers with (better) positioning their work on context-aware pervasive computing. Furthermore, our work reveals the extent of consideration of the contextual dimensions in existing research. In particular it also targets the applications domains that the community works on.

Section 2 will explore the conceptual basis of context and point to related work. Section 3 outlines our approach of analyzing the reflection of context in research practice on pervasive computing. The results of our analysis are presented in Section 4. Section 5 discusses the implications of our results and attempts to provide an explanatory account of the extent of context consideration in research on pervasive computing. Section 6 draws conclusions and provides directions to future work.

2 LITERATURE OVERVIEW

2.1 Conceptual Basis of Context

Over the last 50 years, research has been investigating the concept of 'context' to relate information processing to aspects of the situations in which such processing occurs [5].

Even though the conceptualization of context has continuously been subject of research, there is still a lack of a single, unified definition of context [5]. Dey [14] points out that many people believe to understand the notion of 'context', but they are rarely able to verbally express its meaning or to clearly distinguish context from non-context. Some researchers take a "process" view [9] on context, considering context as an "open concept" [26] which is "dynamically constructed" [17]. Others emphasize that context may always be specified and represented in well-defined domains [10].

Early attempts to define 'context' in the domain of context-aware computing were based on choosing synonyms for context (e.g., [11]) or built on enumerations of examples (e.g., [13, 24]). At the same time, some researchers take a system viewpoint on context (e.g., [22]), while others view context from a user's perspective (e.g., [11]). A common approach for context conceptualization is to divide context into different categories and subcategories [6, 18]; thus, to build so-called 'context models' [3, 5]. Some of the models are highly specific to a certain system or domain (e.g., [6]), others are abstract and generic (e.g., [9]). Frequently, context models were planned as "working conceptualizations" on which the authors could build their own context-aware applications (e.g., [25]).

As a result, the models' scope of categories and subcategories is heterogeneous [2, 5]. This overall observation may reflect that, as Dey and Abowd [15] define, context may be anything that could be used to describe the situation of an entity. The models themselves imply that context may be narrowed down to specified categories, where some models refer to numerous categories and subcategories (e.g., [1, 19, 20]) and some only contain a few (e.g., [18, 21]).

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2.2 Related Work

Several attempts have been undertaken to investigate the understanding of context in the community (e.g., [12]) and to compare and consolidate work on context (e.g., [2, 5, 9]). For instance, Bradley and Dunlop [9] address the multi-disciplinary character of context within different fields and present a consolidated multidisciplinary model of context for context-aware computing. In a comparison of 13 context models[1], Bauer [2] could identify 8 overarching context categories, which she refers to as ‘context dimensions’:

1. location (absolute location, relative orientation, etc.)
2. physical environment (environment, extrinsic, physical environment, etc.)
3. object (identities of objects, etc.)
4. people (user environment, behavior, intrinsic biophysiological state, etc.)
5. social environment (people around, community, social pressure, etc.)
6. activities (service, task, action, etc.)
7. technology (device, computing environment, application, etc.)
8. time (change over time, past-present-future, etc.).

Bauer and Novotny [5] analyzed 36 context models and identified three generic context categories: social context, technology context and physical context. They view activity context as a sub-category to social context and time context as a sub-category of physical context.

A joint conclusion of existing work is that context appears to be a multifaceted concept. Thereby, however, the understanding of context in the community was typically analyzed from a generic viewpoint, such that domain-specific aspects may have been overlooked. Yet, the analysis Bauer and Novotny [5], for instance, could identify domain-specific clusters of context elements, which emphasizes the importance of considering what context elements are associated with and relevant in what application domains.

Furthermore, to date, research on context conceptualization mainly focused on context modeling (e.g., [8]) and context model comparisons (e.g., [5, 9]). Little is known, though, about the understanding of context in the scientific discourse.

Against this background, our work is dedicated to capturing the understanding of context in the discourse of the community and to revealing domain-specific peculiarities as the key for future research on context-aware computing.

3 METHOD

To gain an understanding of context in the discourse of the community, we took a systematic review approach. We collected, categorized, and analyzed the context elements that were mentioned in the scientific discourse of the community over a six-year period.

In all phases of categorizing data, two independent reviewers were engaged. Where disagreement emerged in rare cases, the reviewers discussed the categorization in question, drawing upon further supportive literature or domain expertise on a case by case basis, until consensus could be established.

[1] She calls it “context meta-model”, which is referred to as ‘context model’ in this paper.

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3.1 Sample

We took our sample from the *IEEE Pervasive Computing* magazine. This outlet is a meaningful corpus of pervasive computing research for numerous different application domains and one of the main sources used by the pervasive computing community to obtain knowledge and spread their findings.

We extracted all articles from issue 4(1) to issue 10(2), totaling 414 articles. The following article categories of the IEEE Pervasive Computing Magazine were *included* in the sample: Applications, News, Smart Phones, Spotlight, Standards & Emerging Technologies, Wearable Computing, and Works in Progress. The following article categories were *excluded* from the sample because these are not concerned with the subject matter: Conferences, Education & Training, New Products, From the Editor in Chief, and Guest Editor's Introduction. Out of the 414 articles in the reviewed issues, 297 articles met our inclusion criteria.

3.2 Context Element Extraction and Aggregation

First, we extracted basic citation information from each article in the sample.

Then, serving the purpose of context element identification, two reviewers coded inductively from raw data; i.e., from the full text of the articles. Thereby, they obtained all *explicitly stated context elements* as well as *implicitly stated context elements* from each article.

A context element is considered explicitly stated if the term is explicitly written down in the article. A context element is considered implicitly stated if the context element is circumscribed in the article. While an explicit context element was coded with the element's explicit term (e.g., 'indoor positioning'), a circumscribed implicit context element (e.g., 'rate of the vehicle's speed change') was coded with an explicit element (e.g., 'acceleration and deceleration').

In total, we coded 10,498 context elements with 9,867 elements being explicit and 631 implicit (including duplicates among *different* articles, while duplicate occurrences within one article were filtered).

For eliminating redundancy, we applied a 'term stemming' procedure. Thereby, we united different forms of terms that had the same base form. For instance, the two variants 'locations' and 'location' were united to the code 'location'. This 'term stemming' procedure was applied for both, the explicitly and the implicitly stated context elements. After synonym adjustment and consolidation, conducted by the two reviewers, we finally received a set of 3,741 distinct context elements.

3.3 Context Dimension Assignment

In a next step, based on existing work on context categorization (Section 2.2), the total set of the 3,741 distinct context elements were condensed into dimensions of context on a higher level of abstraction.

We mainly relied on the three context dimensions reflected in existing context models in the literature as identified in the review of context models by Bauer and Novotny [5]: social context, technology context and physical context. Because elements related to activity context were substantially considered in our sample (138 occurrences), we extracted activity context from social context and considered it as an own dimension. The remaining user as well as social environment categories in Bauer and Novotny's social context dimension was renamed to 'social and individual context'. Similarly, context elements related to time were frequently observed in the sample (193 occurences) and we therefore considered time context as a separate dimension from physical context. This resulted in the following five dimensions: physical, social and individual, activity, technology, and time. If a direct assignment of a context element to one of these dimensions had not been possible, the respective element had been

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assigned to the ‘others’ dimension. Overall, each context element was assigned to exactly one dimension (no multiple assignments).

3.4 Application Domain Identification

In addition to coding context elements within the articles, we assigned the articles containing context elements to application domains. An application domain (e.g., healthcare, traffic, household, etc.) is the field or industry targeted by the article. 113 articles (38.05%) could not be assigned to a specific application domain because the papers focused on technological aspects or discussed phenomena generally without referring to any specific application domain.

4 RESULTS

In this section, we present the results of our analysis. First, we provide an overview of the frequencies with that context elements have been observed in research on pervasive computing. Then, we delve into detail how the main six main context dimensions are semantically reflected by several context elements in the discourse on context. Finally, we present how some context elements are particularly related to specific application domains.

4.1 Explicitly and implicitly mentioned context elements

Tab. 1 illustrates that the most frequently mentioned context element was ‘time’ (153 occurrences, 1.45%), closely followed by ‘location’ (146 occurrences, 1.39%). Third to sixth most frequently, the context elements ‘device’, ‘communication’, ‘network’, and ‘infrastructure’ were observed. Comparing explicit and implicit observations shows a dispersed picture.

Table 1: Occurrence cross table of the top six context elements

rank	element	total	explicit	implicit
1	time	153	136	17
		1.45%	1.37%	2.69%
2	location	146	128	18
		1.39%	1.30%	2.85%
3	device	118	111	7
		1.12%	1.12%	1.11%
4	communication	83	83	0
		0.79%	0.84%	0.00%
5	network	79	77	2
		0.75%	0.78%	0.32%
6	infrastructure	77	77	0
		0.73%	0.78%	0.00%
n	…	…	…	…
	sum	10,498	9,867	631

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Consistently with the total number of observations, 'time' was also explicitly observed as most frequent element (136 occurrences, 1.37% of explicit occurrences). Surprisingly, 'acceleration and deceleration' (37 occurrences, 5.86% of implicit occurrences) was the most frequently observed implicit element (see Tab. 2, followed by 'sound' (26 occurrences, 4.12% of implicit occurrences).

Table 2: Occurrence table of the top six implicit context elements

rank	element	implicit
1	acceleration and deceleration	37
		5.86%
2	sound	26
		4.12%
2	proximity	26
		4.12%
4	age	21
		3.33%
5	location	18
		2.85%
6	time	17
		2.69%
n	…	…
	sum	631

Fig. 1 illustrates the number of context elements per article on a time line. While we found significant differences on the number of context elements per issue (F=1.940, p=0.006), which might be due to thematic fluctuations between the issues, the number did not systematically increase or decrease over time (Pearson's r=-0.009, p=0.0872).

Controlling for the relation between the number of authors and the number of elements, articles with a greater number of authors do not consider more context elements (Pearson's r = 0.218, p = 0.391).

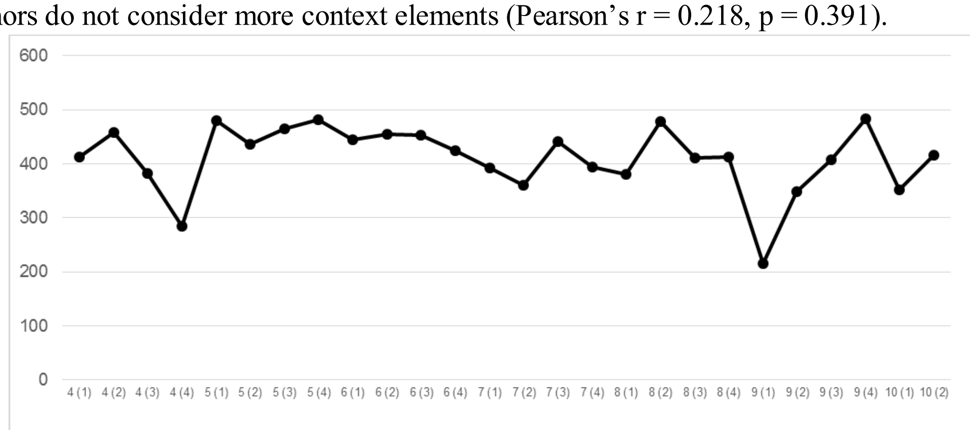

Figure 1: Number of elements per issue on a time line

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4.2 Context Dimensions

As reported in the methods section, our data includes a total of 3,741 distinct context elements that were condensed into dimensions of context on a higher level of abstraction. Fig. 2 illustrates the distribution of context elements among context dimensions.

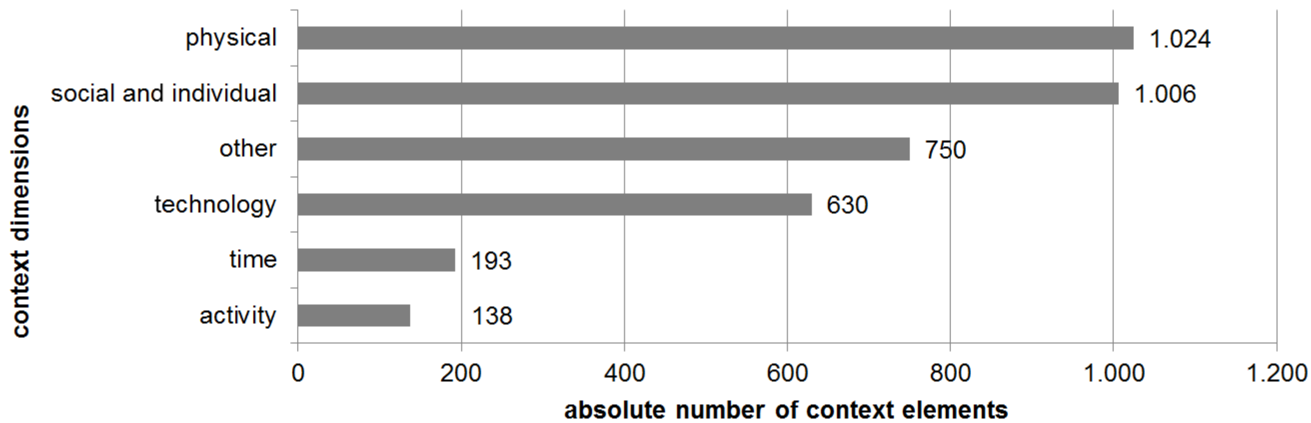

Figure 2: Number of elements describing the context dimensions

The physical context dimension subsumes an array of 1.024 different context elements. The dimension contains context elements related to the physical environment (e.g., acoustics, temperature, etc.), location context (e.g., country, coordinates, etc.), and objects (e.g., vehicle, house, door, etc.).

The social and individual context dimension is described by 1.006 different context elements. For instance, this dimension includes personality traits, people's behavior, physiological aspects, attitudes, and people interacting with other people in organizations.

The technology dimension is also strongly represented (630 context elements). Within technology context many context elements refer to the network context and connectivity of pervasive computing systems (e.g., network bandwidth, signal strength, etc.).

Part of the elements contained in the time dimension (193 context elements) relate solely to temporality (e.g., time of day, duration, period, time interval, time stamp). The remainder relates the time aspect with some other concept (e.g., asynchronicity, delay, lifetime, latency, time pressure) or a specific activity (e.g., shopping time, arrival time, production time).

When analyzing the dimension 'activity' (138 context elements), we identify that a large part of the context elements rather refer to some abstract concept of activity (e.g., action, activity type, task, work) rather than specific activities (e.g., food intake, gaming, smoking). 750 context elements that could not be assigned to a particular context dimension were assigned to the context dimension 'others'.

4.3 Application domains

In addition to context dimensions, we identified 48 application domains that were addressed in the sample; articles concerned with these 48 these application domains contained a total of 3,194 occurrences of context elements (Tab. 3). Within the 48 application domains, we analyzed the distribution of occurrences of the six context dimensions (see Section 4.2).

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The most context elements were observed in articles within the healthcare domain (284 occurrences in 14 articles), followed by medicine (281 occurrences in 18 articles), traffic (252 occurrences in 10 articles) and energy systems (170 occurrences in 7 articles) (Tab. 3, first and second column). Congruently, these four domains were also the domains the most articles in the sample were published about. In 13 application domains (e.g., tourism, service discovery, and user innovation), less than 30 context elements were mentioned in total. On these application domains, few discussions have been taking place in the IEEE Pervasive Computing Magazine, possibly because research on context in these domains is in an early stage and thus very few or only a single article has been published. These 13 application domains with less than 30 occurrences of context provide no reliable evidence of the distribution of the context dimensions.

Overall, the six context dimensions permeate the 48 application domains and the distribution of the context dimensions within the application domains exhibits moderate differences (Tab. 3).

The physical context dimension takes a large proportion in application domains such as agriculture, arctic research, or perishable goods distribution (almost 50% each). Research and also applications in these domains seem to be very concerned with physical goods and the environment. Application domains such as education, cooking, library, or mobile phones have a rather low proportion of the physical dimension in comparison to the other dimensions (below 10%).

The dimension of social and individual context is highly represented in application domains such as family, social networks, public space, and cooking. Cooking, for example, is a manual handicraft activity that can be performed individually or in a social group, such as one's family.

The activity dimension accounts for a much lower share compared to the other dimensions over the analyzed application domains. There are also many domains where context elements associated with the activity dimension are not mentioned at all (e.g., entertainment, computing security, wearable computing). This finding is consistent to the observation that context elements mostly refer to abstract concepts of activity (e.g., action, activity type, task, work). Research tied to particular application domains, though, are likely concerned with particular activities within the domain such as cooking, prototyping a system or lending a book from the library.

The technology dimension has a share of about 20% throughout the application domains. This may be due to all context-aware computing applications requiring context information on a comparable technology baseline, such as the status of Internet connectivity. The computer security domain (58.3%) is a positive outlier because of its tight connection to technology. The family domain (5.6%) makes low use of technology-related context elements.

Similar to the activity dimension, the time dimension is weakly represented throughout all application domains. Television (20.0%) and tourism (16.7%) exhibit the highest shares within this dimension. Time context's low representation across the domains might be due to time being an abstract, intangible concept causing that it is often, but less diversely considered within a specific domain.

The others dimension comprises a heterogeneous set of context elements. This appears to be represented also by the heterogeneous distribution throughout the application domains.

Context dimensions had a share between 0% and 58.3% in the application domains. The maximum of 58.3% technology context was observed in the computer security domain which at the same time exhibits 0% social and individual context. These results seem to be valid and reasonable because in the computer security field systems such as SIEM (security incident and event management) and IDS (intrusion detection systems) take many technology context elements (e.g., network traffic) into account while elements of social and individual context decoupled of the immediate technology environment are less considered within these systems. This observation does not imply that social and individual context is not relevant in the computer security domain, such as for instance

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in scope of security user awareness initiatives. It merely points towards a potential gap that research on context-aware systems has not been taking social and individual context such as security awareness into account so far. In contrast, social and individual context is strongly considered in the family domain (52.8%) which is grounded in interpersonal relationships. In the domain of perishable goods distribution neither technology nor social and individual context was mentioned, but physical context (47.6%) was the most important dimension. Also, this observation is reasonable as the undamaged distribution of perishable goods such as groceries depends upon controlled physical environmental conditions such as a constant temperature.

The distribution of the context dimensions within application domains was surprising in some domains. In the medicine domain, the occurrence of social and individual context was rather low (5.3%) even though human patients play an important role in medicine. Many context elements in the medicine domain was domain-specific taking the particular circumstances of the domain into account. In the firefighting domain, physical context was strongly represented (40.7%) while activity context did not occur and social and individual context was low (3.7%). Despite firefighting services often involve the activity of rescuing a group of people, context addressing the physically harsh environment in which firefighters operate dominate in the discourse.

Table 3: Percentage of context dimensions per application domain

		context dimensions					
application domain	context element occurrences within application domain	others	time	technology	activity	social and individual	physical
healthcare	284	28.9% (82)	13.0% (37)	19.7% (56)	9.2% (26)	14.8% (42)	14.4% (41)
medicine	281	38.8% (109)	10.0% (28)	22.4% (63)	5.7% (16)	5.3% (15)	17.8% (50)
traffic	252	29.4% (74)	10.7% (27)	21.8% (55)	2.4% (6)	6.7% (17)	29.0% (73)
energy systems	170	26.5% (45)	10.0% (17)	30.0% (51)	2.9% (5)	8.8% (15)	21.8% (37)
household	152	22.4% (34)	5.3% (8)	15.1% (23)	7.9% (12)	10.5% (16)	38.8% (59)
developing countries	133	30.1% (40)	5.3% (7)	19.5% (26)	3.0% (4)	17.3% (23)	24.8% (33)
shopping	101	37.6% (38)	14.9% (15)	20.8% (21)	3.0% (3)	8.9% (9)	14.9% (15)
gaming	94	24.5% (23)	10.6% (10)	19.1% (18)	8.5% (8)	17.0% (16)	20.2% (19)
sports	91	38.5% (35)	7.7% (7)	19.8% (18)	12.1% (11)	2.2% (2)	19.8% (18)
robotics	86	38.4% (33)	5.8% (5)	12.8% (11)	9.3% (8)	9.3% (8)	24.4% (21)
music	83	34.9% (29)	3.6% (3)	21.7% (18)	2.4% (2)	16.9% (14)	20.5% (17)
public space	83	31.3% (26)	4.8% (4)	14.5% (12)	8.4% (7)	24.1% (20)	16.9% (14)
office	75	25.3% (19)	10.7% (8)	33.3% (25)	8.0% (6)	6.7% (5)	16.0% (12)
arctic research	71	31.0% (22)	8.5% (6)	11.3% (8)	0.0% (0)	2.8% (2)	46.5% (33)
personal information management	67	32.8% (22)	10.4% (7)	11.9% (8)	11.9% (8)	13.4% (9)	19.4% (13)
agriculture	66	25.8% (17)	4.5% (3)	16.7% (11)	0.0% (0)	6.1% (4)	47.0% (31)

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education	64	48.4% (31)	9.4% (6)	20.3% (13)	1.6% (1)	14.1% (9)	6.3% (4)
advertising	61	27.9% (17)	21.3% (13)	14.8% (9)	3.3% (2)	16.4% (10)	16.4% (10)
Second Life	55	30.9% (17)	5.5% (3)	25.5% (14)	5.5% (3)	10.9% (6)	21.8% (12)
airport services	54	37.0% (20)	11.1% (6)	16.7% (9)	5.6% (3)	1.9% (1)	27.8% (15)
firefighting	54	24.1% (13)	11.1% (6)	20.4% (11)	0.0% (0)	3.7% (2)	40.7% (22)
difficult environments	46	34.8% (16)	2.2% (1)	10.9% (5)	4.3% (2)	6.5% (3)	41.3% (19)
digital media	46	34.8% (16)	10.9% (5)	23.9% (11)	0.0% (0)	4.3% (2)	26.1% (12)
public transport	44	36.4% (16)	11.4% (5)	11.4% (5)	4.5% (2)	22.7% (10)	13.6% (6)
perishable goods distribution	42	38.1% (16)	9.5% (4)	0.0% (0)	4.8% (2)	0.0% (0)	47.6% (20)
emergency equipment	40	45.0% (18)	5.0% (2)	7.5% (3)	2.5% (1)	15.0% (6)	25.0% (10)
television	40	40.0% (16)	20.0% (8)	17.5% (7)	5.0% (2)	2.5% (1)	15.0% (6)
pollution	37	16.2% (6)	5.4% (2)	18.9% (7)	2.7% (1)	16.2% (6)	40.5% (15)
family	36	11.1% (4)	8.3% (3)	5.6% (2)	2.8% (1)	52.8% (19)	19.4% (7)
cooking	35	37.1% (13)	2.9% (1)	8.6% (3)	17.1% (6)	25.7% (9)	8.6% (3)
library	35	31.4% (11)	2.9% (1)	31.4% (11)	17.1% (6)	11.4% (4)	5.7% (2)
social networking	33	15.2% (5)	24.2% (8)	15.2% (5)	3.0% (1)	30.3% (10)	12.1% (4)
industry	31	45.2% (14)	9.7% (3)	12.9% (4)	0.0% (0)	3.2% (1)	29.0% (9)
entertainment	30	33.3% (10)	6.7% (2)	16.7% (5)	0.0% (0)	13.3% (4)	30.0% (9)
tracking and tracing	30	33.3% (10)	6.7% (2)	23.3% (7)	0.0% (0)	30.0% (9)	6.7% (2)
wearable computing	28	42.9% (12)	3.6% (1)	10.7% (3)	0.0% (0)	3.6% (1)	39.3% (11)
outdoor workplaces	27	33.3% (9)	3.7% (1)	37.0% (10)	3.7% (1)	7.4% (2)	14.8% (4)
prototyping	26	26.9% (7)	3.8% (1)	15.4% (4)	15.4% (4)	7.7% (2)	30.8% (8)
computer security	24	16.7% (4)	16.7% (4)	58.3% (14)	0.0% (0)	0.0% (0)	8.3% (2)
engineering	24	16.7% (4)	8.3% (2)	37.5% (9)	4.2% (1)	20.8% (5)	12.5% (3)
military	23	17.4% (4)	4.3% (1)	47.8% (11)	4.3% (1)	8.7% (2)	17.4% (4)
mobile phones	23	34.8% (8)	13.0% (3)	39.1% (9)	4.3% (1)	4.3% (1)	4.3% (1)
surveillance	22	36.4% (8)	0.0% (0)	22.7% (5)	9.1% (2)	9.1% (2)	22.7% (5)
disability	21	19.0% (4)	0.0% (0)	28.6% (6)	4.8% (1)	4.8% (1)	42.9% (9)
Internet	19	26.3% (5)	10.5% (2)	36.8% (7)	0.0% (0)	10.5% (2)	15.8% (3)
user innovation	19	36.8% (7)	5.3% (1)	31.6% (6)	0.0% (0)	26.3% (5)	0.0% (0)
service discovery	18	44.4% (8)	11.1% (2)	22.2% (4)	11.1% (2)	11.1% (2)	0.0% (0)
tourism	18	38.9% (7)	16.7% (3)	11.1% (2)	5.6% (1)	27.8% (5)	0.0% (0)

5 DISCUSSION

This study explored how context is reflected in the research discourse on pervasive computing. First, we discuss our findings and about the consideration of context in the pervasive computing community. Then, we aim to move towards potential factors explaining the extent of consideration of context in the pervasive computing community.

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5.1 Consideration of context in pervasive computing and implications

Our results emphasize that context is discussed heterogeneously and in a multi-facetted manner within pervasive computing. Within each of the six context dimensions identified (physical, social and individual, technology, time, activity, other) an array of diverse context elements is discussed. Each context dimension covers between 138 and 1.024 different context elements. For instance, within the physical context dimension, context related to weather (e.g., sun radiation) and the characteristics of material objects (e.g., transparency) are discussed.

Although the most mentioned elements (e.g., time, location) occur rather frequently, the low percentages of total occurrences of these context elements in the entire sample (2.84% for time and location) indicate that context is a multifaceted concept. Context elements related to locational aspects (e.g., cardinal coordinates, region, distance, etc.) were most frequently mentioned (in total 408 occurrences). The relative popularity of location context in pervasive computing may be due to a plethora of location-based services available and the widespread propagation of location sensing technology such as GPS in devices [16, 29]. Despite its high popularity, location context only accounts for 3.9% of all occurrences of context in the sample. Context-awareness in pervasive computing is not pillared upon few single context elements such as location. Rather, the context considered in pervasive computing is highly diverse.

Even though all of the analyzed context dimensions are multi-facetted, the physical as well as social and individual dimensions of context are even more diversely discussed. We could identify 1.024 different context elements within the physical context dimension and 1.006 within the social and individual context dimension. 77.5% of them (e.g., parasitic mobility, olfactory smell, panic) occur only once in the sample. They exceed the usually considered granularity of context elements in work on conceptualizing context, such as 'user context' and 'light level' [9, 18, 21, 27]. These results indicate that the discourse on context in pervasive computing is spread across a big long-tail of highly diverse context elements. The wide variety of context dimensions and elements considered supports the statement that context may be "any information that can be used to characterize the situation of an entity" [25].

Information theory [25] would suggest that dimensions having a medium number of context elements have the lowest entropy and therefore should be most *informative*. Dimensions with a high number of context elements are rather broad and complex and, thus, difficult to operationalize. Dimensions with a relatively low number of context elements may be narrowly defined with rather generic elements.

Within application domains, the context dimensions we have identified are considered with different amplitude. For instance, physical context accounts for almost half of the context considered within the perishable goods distribution (47.6%) and agriculture (47.0%) domains, but only for 5.7% within the library domain. This observation might be explained by the physical environment (e.g., weather, rain) being crucial for successfully growing and harvesting agricultural goods and distributing them accordingly (e.g., climate control for transportation, cooling). Libraries, in contrast, mainly depend on information products that can be managed, hosted or even distributed electronically, pushing the importance of the physical environment into the background. Even though there are moderate differences in the consideration of the context dimensions between the application domains, no strikingly superjacent imbalances were observed. Rarely any context dimensions were considered by majority (i.e., greater than 50%) in the application domains. If a context dimension was considered slightly more than 50% within an application domain (58.3% technology context for the computer security domain, 52.8% social and individual context for the family domain), they were clearly not dominant. The other context dimensions still play considerable roles in the discourse on context-awareness within the respective application domains.

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A long-tail of context elements and differences between the consideration of context in various application domains suggest that the discourse on context in pervasive computing is not only driven by available and functional sensing technology. Rather, other factors taking the particularities of the application domain, the goals of context-aware systems and the development process into account may influence the discussion considerably.

Our findings indicate that the discourse on context is rather explicit and clear, naming the involved specific context directly. Context is more often referred to explicitly (9,867 explicit occurrences) compared to implicit references (631 implicit occurrences). In the discourse on context, explicit references may be more often used in case the context under consideration can be named and labelled. The ability to name and label concepts may indicate that clear and tangible conceptions of them exist.

Also, the context elements contained in the data's long-tail are specific and nuanced, for example 'acoustic sensitivity' and 'skin temperature', rather than only gross-grained and vague, such as 'context' and 'physical'. Context is described by specific terms rather than generic terms only. Explicit and specific references to context would imply that context is a well comprehensible and conceivable concept in pervasive computing. We conjectured that the comprehension of context evolved and expanded within the community over time going hand in hand with novel technological possibilities. Hence, on a time line, we expected that with technology advancement researchers would have included more and more context elements in their research. However, analysis did not show any trend over time. We conjecture that, in the early years, researchers presented their great visions (such as Weiser [9, 27] did) and, thus, already mentioned lots of context elements in their articles.

Our results imply that different types of sensing approaches are required for context-aware systems to gather the multi-facetted and highly heterogeneous context discussed in pervasive computing. In addition to hardware sensors, also logical and software-based sensors may be used by context-aware pervasive computing systems to gather context information. For example, hardware GPS sensors are able to capture the Cartesian coordinates of a user. For reasoning about the symbolic location of the user, logical sensors might provide additional information. For instance, logical sensors can take information from the web and the user's personal calendar into account to reason that the user is located 'in the kitchen' or 'at work'. Also, our findings on the explicitly and implicitly of context elements and the level of granularity in the discourse implies that the pervasive computing community has different requirements on the quality, specificity, precision and accuracy of provided context information.

5.2 Potential factors explaining the extent of context consideration

The varying extent of consideration of specific context dimensions in context-aware computing may be due to several reasons (see Fig. 3).

First, the availability, deployment and cost of sensor technology may be pivotal. If sensor technology for a context element is highly available on the market, it is more likely that research and practice will consider the respective element. Because of a more widespread market availability of sensors, they are easy to procure and build into context-aware systems. Similarly, if a context element is highly deployed in context-aware systems, then it is likely that the respective element is highly considered. Accordingly, a higher research interest in context elements that can be sensed by these sensors is likely. In contrast, if the cost for sensors required gathering a context element is high, researchers and practitioners will rarely consider this element.

Second, the information dimension of a context element drives its consideration. Some context elements require combining multiple pieces of information, potentially to be gathered from multiple sensors, to gain the context elements' value. For example, a weather-dependent system may need to combine data on air pressure, rain,

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sunshine and temperature to gain a meaningful state of the context element 'weather'. Hence, the context-aware system needs to combine multiple context data and higher-level processing of simpler context elements. Therefore, gathering the context element is more complex and its consideration is more likely to be low. Similarly, if the complexity of the required data structure for representing the data connected to a context element is high, it will also be less likely considered.

Third, the aspired accuracy and purposes of a context-aware system may influence consideration of context elements. If a context-aware system requires high accuracy of context sensing, then it may achieve more information about its context by taking more context elements into account. A weather-dependent system, for example, that combines data on air pressure, rain, sunshine and temperature will have a more accurate context information about weather compared to a system which only considers the context element temperature. The more purposes a context-aware system aims to serve, the more likely it is required to take a higher diversity of context elements into account. For example, virtual personal assistants, such as those offered by Amazon and Google, serve multiple purposes including to play personalized music, to retrieve information from the web and to control functions in a smart home. These assistants are likely required to take a combination of diverse context elements relevant to the music, entertainment, personal information management as well as household and smart home domains into account.

Fourth, the system design process may influence the consideration of context elements. If application designers' creatively combine a diverse number of context elements in the system design process, it is more likely that context elements are highly used. Similarly, if system designers try to tailor a context-aware system particularly to user value, a higher and more diverse consideration of context elements can be expected.

6 CONCLUSION

The purpose of this paper was to investigate, how context is reflected in the discourse on pervasive computing and to shed light on the application domains in which different aspects of context are considered. We aim to support industry specialists, professionals, and researchers working within these application domains in positioning their work. By analyzing 297 articles from IEEE Pervasive Computing Magazine, we could demonstrate that context is discussed as heterogeneous and multi-facetted concept within the realm of pervasive computing.

Among the six context dimensions, we could identify, physical context as well as social and individual context were most frequently reflected in the community's discourse. The discourse on context in pervasive computing is distributed across a big long-tail of many heterogeneous context elements. The community refers to these context elements mostly specifically and explicitly rather than generically and implicitly indicating that it has clear and tangible conceptions of context.

We further contributed by unveiling the heterogeneous reflection of context dimensions within research on different application domains of context-aware computing such as healthcare, medicine, traffic, and energy systems. Industry specialists, professionals and researchers working within these application domains receive targeted guidance on which context dimensions are particularly well considered and important within their field.

Based on our results, we conclude by theorizing that the extent of consideration of context in pervasive computing depends upon the availability, deployment and cost of sensor technology, combination and complexity of context information, required accuracy and purposes of context-aware systems as well as creativity and focus on user value in the system design process.

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A limitation of our work is that it only considers context within application domains which have been primarily addressed in the reviewed articles. The context dimensions may also be considered in additional domains and industries that have not reported about developments, concepts, context-aware applications, use-cases, technologies and standards in their domain.

While our work's main focus was on the research discourse of the community on context in pervasive computing, future work will have a closer eye on whether there is a difference between research's discourse and vision about context in an application domain and what can be actually realized by technology within a domain already.

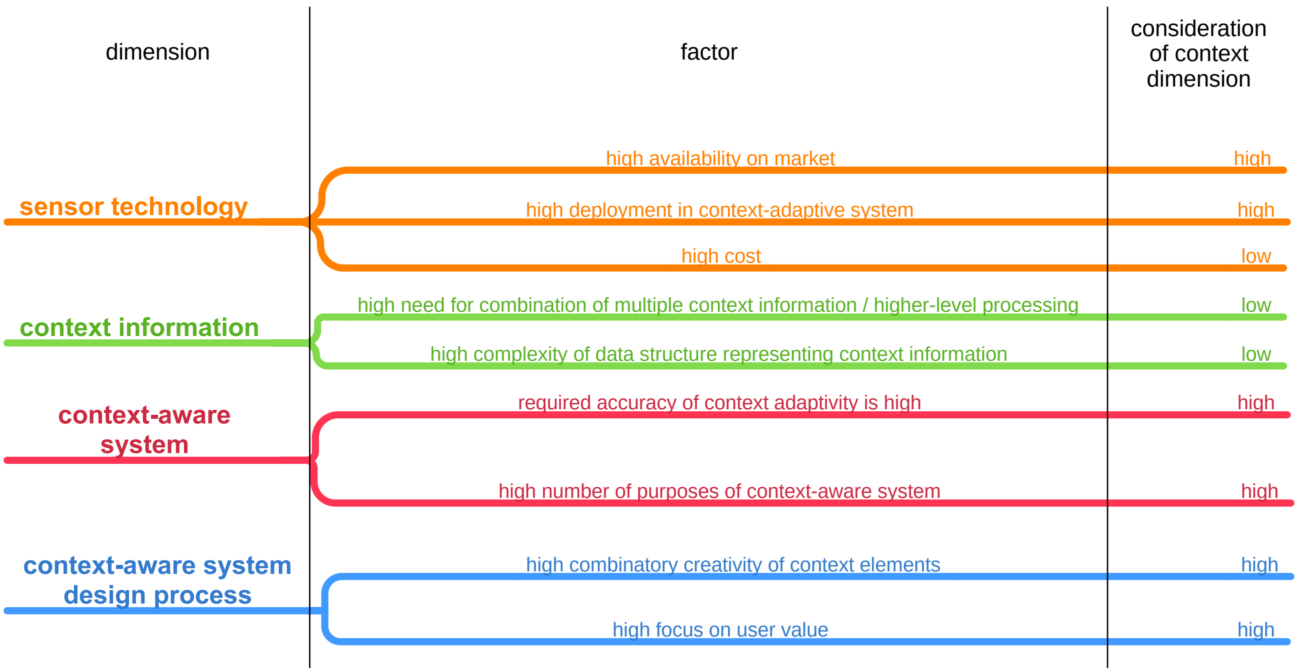

Figure 3: Factors of low and high consideration of context elements in pervasive computing.

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