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Considering cognitive aspects in designing cyber-physical systems: an emerging need for transdisciplinarity

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Abstract. With the rise of smart systems, ubiquitous computing and cyber-physical systems, information-intensiveness of products increases and users become challenged – possibly even overloaded – with expanding options and possible interactions. The number of possible variations of user-operation sequences can rapidly escalate and for designers it becomes difficult to foresee all possible outcomes, which might include unacceptable performance, failure, and even fatalities. In this paper we show how model-based theories from cognitive science – in particular cognitive architectures and mental models – can be deployed in the design of these products and systems with the objective to reduce the risk of unwanted cognitive effects and realize a more symbiotic relationship between users and systems. We argue that the deployment of such models requires a transdisciplinary approach in which designers intensively cooperate with cognitive scientists and end users.

Keywords: cognitive engineering, mental models, cognitive architectures, cyber physical systems, information-intensive products

1 Introduction: consideration of the cognitive aspects of cyber-physical systems from a transdisciplinary perspective

1.1 Cyber-Physical Systems (CPSs)

A current trend in industrial design engineering is the development of products that can be regarded as cyber-physical systems (CPSs). Cyber-Physical Systems have been defined as *integrations of computation with physical processes*, in which embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa [17]. CPSs are closely related to the 'internet of things' (IoT) [13], and 'Meta-products' [14]. Typically, CPSs have to be considered in the context of ubiquitous/pervasive computing, ambient intelligence, the 'disappearing computer' and the post-PC area [19]. It means that (i) information will be available anytime, anywhere, (ii) computing and communication devices and communication technology penetrate into our everyday life and environment, (iii) not PCs but systems of very small or even invisible artefacts with processors are executing software while also communicating with each other. In addition, products may communicate with their users and environments and they may have cognitive capabilities of their own.

CPSs are often deployed in the context of product-service systems [9]. As a consequence of their complexity, the design process of CPSs involves several aspects of product design (electronics, software, interface, communication, mechanics, robotics, industrial design, etc.), but typically also task design, organisation design and service design.

The main disciplines involved in designing CPSs are Industrial Design Engineering (IDE), Cognitive Psychology, Psychophysiology, Information and Communication Technology (ICT) and of course the disciplines that are commonly involved in the interdisciplinary faculty of IDE such as Materials and Production Technology, etc. In predecessors of CPSs, being for instance mechatronic systems and smart systems, the disciplines of ICT and physics were already heavily involved. Integrating cognitive psychology issues will be a key challenge in the near future of CPS development.

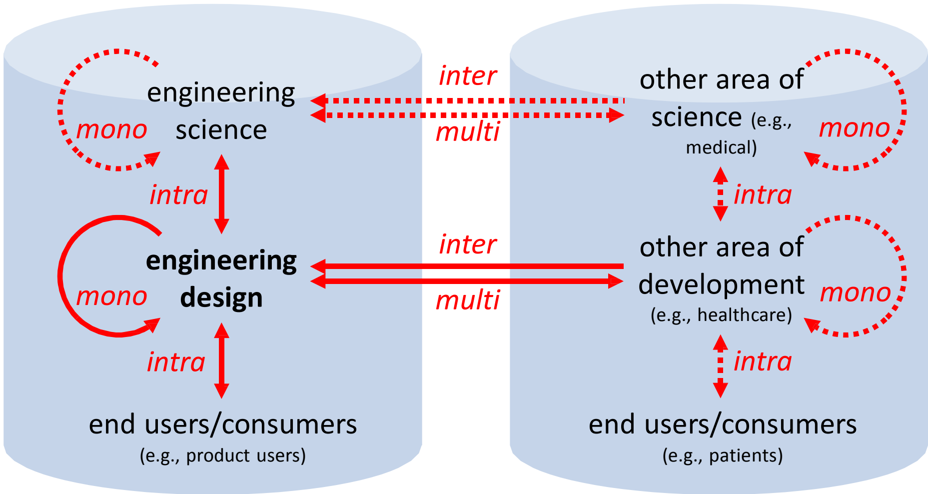
1.2 CPSs and Transdisciplinarity

It has already been argued that CPSs require a transdisciplinary approach [14], or interdisciplinary, multidisciplinary and transdisciplinary at the same time [13]. According to Horváth and Gerritsen in [13], *interdisciplinarity* involves two knowledge domains (for CPSs: the cyber and physical domains), *multidisciplinarity* involves more than two knowledge domains (for CPSs, additional domains such as biological, engineering and information sciences can be considered), and *transdisciplinarity* extends the knowledge from the various domains towards implementation and application, for instance by providing architectures and technologies to realize the artefacts and services within the CPS. This CPS-specific interpretation of transdisciplinarity seems to be in agreement with Pohl's description of transdisciplinary *research*, which he says 'is not only about producing knowledge but it is also problem- and solution-oriented, and the research results are translated into usable products' [22].

Generalizing these statements regarding the various 'disciplinarities', we have concluded that they aim to describe different types of *collaborative professional activities* in two dimensions, one dimension being that of the different domains, disciplines or areas (such as healthcare, agriculture, education) and the other being the conventional knowledge value chain, *research* → *design & development* → *application*, although other chains have also been suggested [20]. The collaboration aspect, as is also underlined by Wickson et al. [29], signifies that the intensity of the work requires mutual interactions between stakeholders over the concerned dimension(s), rather than that they access prepared knowledge from each other's domain – e.g., from books.

In addition to consulting literature concerning the crossing of disciplinary borders in projects, we can learn from literature concerning the crossing of geological borders by companies, where the analogous terms international, multinational and transnational are commonly used. In that context, an often cited set of definitions has been put forward by Bartlett [6, 7]. In our context, the *differences in handling knowledge* that he

Fig. 1. Illustration of the meanings of *mono-disciplinary*, *interdisciplinary*, *multidisciplinary* and *intradisciplinary*, reasoning from the field of engineering design



has identified are the most relevant: *international companies* operate in multiple countries with knowledge developed at a central location and transferred to overseas units, *multinationals* develop and retain knowledge within each unit across multiple countries, and *transnationals* develop and share knowledge worldwide.

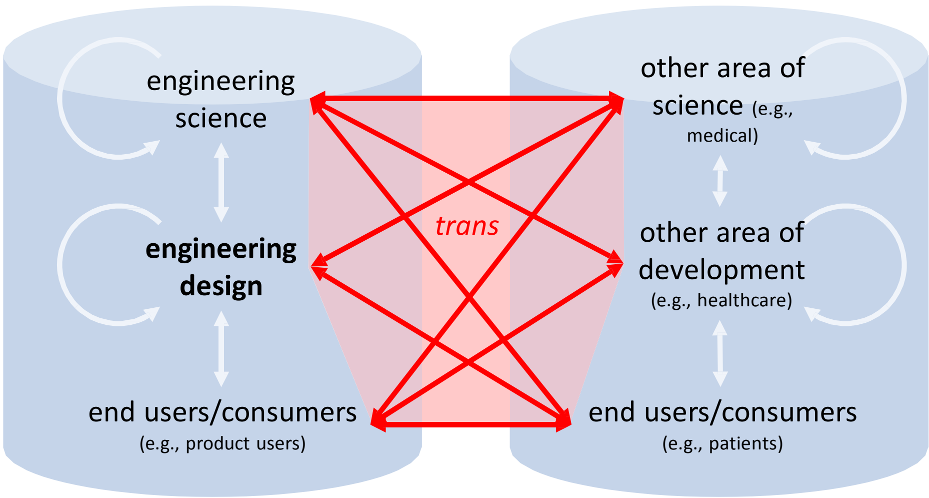
Based on the above assertions we have defined the different 'disciplinarities' as follows:

Mono-disciplinarity (mono- from Greek μόνος: *alone*, *only*) is confined to one domain, at one level of the knowledge value chain. An example is a project in which domestic-appliance engineers and designers are developing a coffee maker on their own. Knowledge from science or from users is only used in an input-only fashion, e.g., from textbooks or available user surveys.

Intradisciplinarity (intra- from Latin *within*) involves collaboration at multiple levels within the same domain. As an example, domestic-appliance engineers and designers are developing a coffee maker in close collaboration with end users and/or food scientists.

Interdisciplinarity (inter- from Latin *among*, *between*) and ***multidisciplinarity*** (multi from Latin *many*) are based on collaboration between different domains at one level. In interdisciplinarity one domain acts as a core domain, coordinating the other domains that supply contributions from their fields. Multidisciplinary collaboration is decentralized in that each involved discipline manages its own activities, based on cooperative central coordination. Consider for example, a project in which domestic-appliance engineers and designers are developing a product in cooperation with a medical company to design a pill dispenser for consumers (who may be also patients). In the case of interdisciplinary design, the medical company acts as the principal and

Fig. 2. Various forms of transdisciplinarity (elaborating on Fig. 1).



the dispenser has to conform to a given design of the pills or their packaging, whereas in the case of multidisciplinary design both parties deliberate over the requirements and specifications for both the dispenser and the pills.

Fig. 1 illustrates how we have interpreted these first four 'disciplinarities', taking the profession of engineering design as a starting point for reasoning.

Transdisciplinarity (trans- from Latin: *across*) implies collaboration at multiple, or even *all* [20], levels in two or more value chains. This is shown in Fig. 2, where collaboration should span at least one of the diagonal arrows or two of the horizontal arrows. In addition transdisciplinary (TD) activities may be inter-/multi-/intra-disciplinary at the same time. As TD *research* has been defined as research involving translation of research findings into solutions (i.e. design), we can reason that TD *design* strongly depends on collaboration with researchers and/or end users. This suggests that there is no distinction between TD design and TD research and that it may be better to speak of TD projects or activities. In addition to the *relational* aspect of collaboration, we also consider the level of *maturity* of the connections between distinct disciplines relevant in characterising transdisciplinarity. Typical TD projects are *pioneering* efforts to connect domains. If relations become established over time, a new 'vertical' discipline is formed, and projects are no longer TD.

It has to be noted that the above definitions give an oversimplified view on the subject matter. Firstly, disciplines can be considered at various levels of abstraction. Therefore, the scope of 'disciplinarities' also depends on the level of abstraction chosen by the observer. Engineering for instance has many subdomains. At a lower level of abstraction a design project involving mechanical and civil engineering can be considered interdisciplinary, whereas it would be mono-disciplinary according to Fig. 1. Secondly, more layers can be distinguished in the knowledge value chain than the figures show. For instance, between *engineering design* and *end users/consumers* one could think of *manufacturing*, *distribution*, etc. Likewise, in the medical chain on the right hand side a layer *doctors* between *development* and *end users/consumers*, or even parallel to *development* can be added. These additional layers could all be involved in interdisciplinary and TD projects. The number of layers in a chain can differ and it is not always obvious which ones are on the same level. As a third and final remark, the lowest level in the chain does not always show clearly distinct domains: a consumer who buys a coffee maker at one time can be a patient at some other time.

1.3 Cognitive aspects and issues of CPSs

In this paper we have chosen to focus on one typical characteristic of CPSs that we think requires a TD approach, namely that, in the way they are designed and the ways in which they function, CPSs address issues of *human cognition* as well as *artificial cognition*. CPSs will increase the level of communicative and knowledge conversion technologies built into consumer products and systems. It means, on the one hand, that CPSs can take over particular cognitive tasks from users. For designers of CPSs, this opportunity raises the question how to allocate cognitive tasks between user and CPS, and how outputs of CPSs can be designed such that they are relevant for users.

On the other hand, CPSs are part of the information society that produces ever-increasing amounts of available information, both valuable and useless. It means that despite the possible reduction of cognitive tasks that they may offer, CPSs may also cause an overall increase in the amount of information exchange with users. The increase of information may negatively influence use comfort, and in demanding situations cause perceptual and/or cognitive overload. In addition, it is expected that, since they offer functionalities that cannot be realized with conventional technology, CPSs will increasingly be deployed in safety-critical situations [16]. From conventional safety-critical systems, such as nuclear plants, it is known that their evaluation involves identification of rarely occurring scenarios, e.g., with a probability of once in 1,000 years [8]. In many circumstances where CPS will play an increasingly important role, such as car driving, air traffic and medical care [5, 18, 30], we also have to consider infrequent scenarios (e.g. with a probability of perhaps once in 500 years per driver/pilot/physician) in order to assess the likelihood of accidents or fatalities. This is only possible if we also have a comprehensive understanding of human cognitive behaviours under varying situations including emergency or stressful scenarios [23].

We believe that this increased understanding will eventually enable designers to realize a level of cognitive symbiosis between CPSs and humans, from which not only safety-critical CPS but also CPS supporting everyday life, will benefit – for instance by increasing user comfort and satisfaction. The importance of achieving symbiosis is expected to increase with the level of interaction between humans and the CPS and is arguably less important for autonomous CPS acting without any human intervention.

The desired symbiosis is likely to require intensive use of knowledge from cognitive sciences. Especially now, in the early days of CPSs, no ready-made design tools are available to realize symbiosis, and we claim that it will require TD collaboration with scientists from these other fields. In addition it is also likely to require intensive involvement of end users, both in research and in design activities. It is expected that TD collaboration will pose several challenges to the stakeholders involved, especially because the collaboration spans across the knowledge value chain *and* various domains. Therefore it is likely that we have to deal with (i) different jargons used by experts of electronics, software, interface, communication, mechanics, robotics, industrial design, (subdomains of) cognitive science and other domains, (ii) different work attitudes of the people involved (e.g., synthesis-oriented and result-driven vs. analytical and curiosity-driven), and (iii) different ways of evidencing and validating the outcomes of the work (e.g., calculations vs. empirical testing).

In this paper we will briefly discuss two directions of research in which we aim to study how knowledge from the cognitive sciences can be used in cyber-physical product development processes, addressing the above issues at two levels. The first one, introduced in Section 2, aims to use *cognitive simulations* in order to identify potential bottlenecks for human information processing as well as options to resolve them. In this context it is assumed that the CPS and its use scenarios have been worked out to such an extent that they can be modelled and simulated. The second direction of research, introduced in Section 3, addresses the issues at a higher level in order to support the early stages of designing CPSs. The aim is to gain operational knowledge on *mental models* that can be used to design better informing systems. People use cognitive representations in order to characterize, understand, reason and predict the surrounding world. A class of these representations are called mental models (MMs). Designers of informing systems need predictive power on the knowledge and reasoning patterns of potential users of their systems. The concept of MMs, is expected to provide the basis for the minimal required understanding of the human reasoning.

As authors of this contribution, we are operating at the science level in Fig. 1/2 in both of these initiatives. Our interest is to investigate new ways of supporting designers. Our work combined with contributions by designers who implement the results represents the 'design engineering' side of the projects. In Sections 2 and 3 we will mostly focus on explaining on the cognitive-science involvement.

2 Simulating cognitive loads and processing times

In the first project we conceptualized a plan together with cognitive scientists to develop an approach for simulation of human mental processes together with models of products and systems. The goal is to evaluate CPSs during development, in order to identify bottlenecks that need to be resolved by adapting the design – i.e., the design of the system, the design of human tasks or the related service design.

We propose to test CPSs without humans in the loop by using a *cognitive architecture* (CA) as a model that simulates human information processing and decision making.

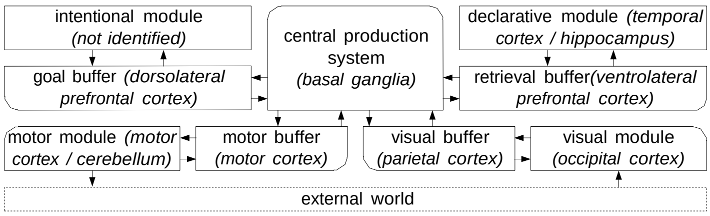
One project concerns simulation of centralised control rooms for pound locks, which our government agency of public works and water is planning to operationalize from 2014 onwards. In the terminology of Poovendran [23], this is a 'nascent' CPS with important roles for intensively connected cyber components (sensor-data processing, control, communications, etc.) and physical components (lock gates and moving bridges, etc.) but lacking the advanced characteristics of tomorrow's CPSs, where cyber capabilities are embedded in physical processes and components, where networking is employed at multiple and extreme scales, etc. A more advanced CPS to which we give consideration for conceptualization and study is a system for support of emergency response in blocks of buildings. Emergency management is currently supported by several systems, tools and equipment, some of which operate in connection in order to facilitate a variety of situations, including detection of fire, offering medical assistance, communication with fire-fighters/paramedics/police and managing evacuations. Although some of today's systems and products are technologically quite complex, we see considerable potential in further integrating and enhancing them based on cyber-physical technologies, e.g., advanced detection based on sensor networks, intelligent proactive assistance and ad-hoc communication networks. As a matter of course, such enhancements are also a future option for the pound-lock control system. For emergency response, systems with some of these technologies have already been prototyped, but so far mostly focusing on victim monitoring by medical professionals at large-scale disaster sites [e.g., 12]. We expect to face additional challenges when having to deal with factors such as non-expert volunteers, evacuation of buildings and isolated but more frequently occurring incidents as well as drills.

Both the pound-lock control system and the emergency response system nicely illustrate the potential of our approach for CPS designers because they are safety-critical, and the cyber-physical system acts in close cooperation with human operators who are still in charge of important decisions. The operators have a high responsibility to act according to protocols that involve taking into account many different factors. For the pound-locks this includes dealing with various lay-outs of locks, types of boats and skippers, weather circumstances, etc. In addition, most locks have multiple chambers, in connection with which the newly introduced procedure of 'zipping operation' increases the operators' multitasking load. In exceptional cases, cognitive processing errors by operators may lead to severe accidents (colliding ships) or even disasters (flooding). Likewise, members of the emergency response team have to make split-second decisions for instance about which actions they can perform themselves and which ones are best left to fire-fighters and paramedics – in a wide range of situations including possible heart failure and escalation of a fire, which can obviously present themselves as matters of life and death.

Due to the limitations of real-time simulation, it is impossible to test all the possible combinations of factors and sequences of occurrence in an interactive simulator. However, by combining simplified system models with ACT-R (adaptive control of thought–rational) – a CA that has proven to produce accurate, scientifically validated simulations of the relevant phenomena, i.e., multitasking, cognitive overload, distraction, fatigue, memorising and learning, etc. [25] – we expect to run the simulations much faster than real-time, so that even rare critical situations can be revealed [27].

CAs are blueprints of cognition based on findings from brain science. Fig. 3 shows ACT-R's modules and the identified corresponding areas in the human brain [3]. The *external world* block corresponds to everything outside the human. In our pond lock example it would comprise the operation interface, the locks themselves with related

Fig. 3. Modules of ACT-R and corresponding cortical regions (*in italics*).



constructions (bridges, traffic lights, etc.) and, based on available statistics, the traffic and the weather. The connection between ACT-R and the external world is established through the motor module (human output through control of limbs) and visual module (human input through visual perception). In case of aural input, an aural module is included as well.

Simulation models in ACT-R are always custom-built for a specific case. Each module is 'filled' with routines programmed in LISP [21] describing information-processing behaviour related to specific subtasks. For common subtasks, LISP routines are readily available; for others, laboratory studies with human subjects have to be conducted in order to collect data for new routines. The overall task of the human, e.g., the protocol for operating pond locks, is written as a LISP routine for the intentional module.

Laboratory experiments and programming of routines are activities that require expert knowledge about cognitive information processing. Therefore, in its current form ACT-R is scarcely used outside the cognitive science domain and it is not an off-the-shelf simulation tool for designers. Consequently, its embedding in design calls for a TD approach in cooperation with cognitive scientists.

In this cooperation there is also a strong aspect of *pioneering*. Although application of CAs has already become more practical – evolving from puzzle-solving i.e., pure brain exercises with 'disembodied' CAs lacking visual and motor modules [4], through interactions with software via mouse, keyboard and monitor [10], to specific tasks in aviation [11] and car driving [24] – they have not yet been applied in interaction with complex multi-faceted models of the external world, despite the obvious potential benefits. A possible explanation is that, on the one hand designers are not aware that it is actually possible to simulate mental processes, and that on the other hand cognitive scientists come from a research tradition focused on controlled experiments that benefit from simple external worlds. To promote pioneering in TD projects, we therefore have to facilitate designers in finding research efforts that can contribute to their work, and find ways to make researchers benefit from practical applications. In the case of pond lock simulations, this might involve developing validation methods for outcomes like 'once in 1,000 years, a cognitive operator error will cause a flooding', which cannot be straightforwardly verified in a controlled experiment.

The investigation of mental models in the next section involves cooperation with cognitive scientists as well. However, cognitive architectures and mental models require different investigative approaches (laboratory measurements vs. interviews), and the scientists involved belong to distinct communities.

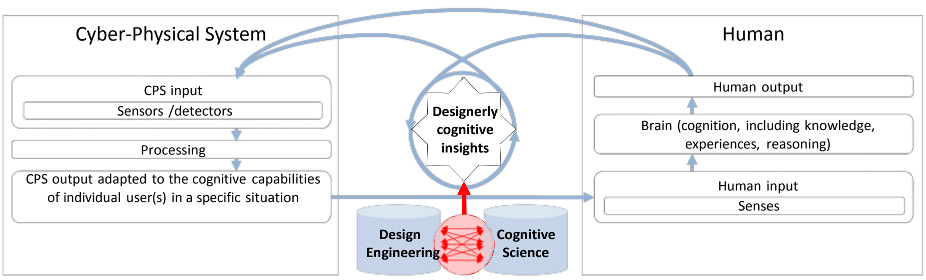
3 Realizing awareness of mental models in cyber-physical systems

The second direction of research focuses on so-called *informing CPSs* and aims to find novel means to inform users and to find new symbiotic relations between human and cyber-physical systems, based on which designers can be supported in the early stages of CPS development. Here, the objective is once again to avoid situations where users are mentally or perceptually overloaded. In cognitive psychology the internal representation that people hold of an external reality that allows them to explain, interact, and predict that reality is called an MM. Mental models have been identified as a basis of human reasoning [15]. This makes the phenomenon an interesting starting point to consider in designing the human interface of systems. The purpose of this project is to gain a better understanding in the manner in which MMs influence our interaction with the informing part of CPSs, and to provide guidelines for designers based on these insights (Fig. 4). The project will therefore produce a predictive theory and additionally formulate its affordances for the design process.

For this project, new insights are needed about the operation of MMs, as well as on how, for our specific design objective, the real-life operationalization of MMs is influenced by informing. We have assumed that the highest need for adapting the level and content of the provided information will be in critical situations that cannot be anticipated straightforwardly. Therefore, the objective of the first research cycle is to address this problem by deriving a definition of MMs which, in contrast to already existing definitions, will be tailored to critical events. Since the definition has to be both meaningful in our specific context of designing highly adaptive informing CPSs and correct regarding its psychological fundamentals, the disciplines of design engineering and cognitive psychology have to be brought together.

The expertise from cognitive psychology was initially adopted from selected relevant scientific papers: 125 published descriptions of MMs have been decomposed to a set of attributes, and each attribute has been assessed to see if it was associated with critical events, or not. This exploration provided a large number of attributes for a new MM definition. Based on the top-rated attributes, a definition was synthesized as a starting platform to investigate the influence of informing on decision-making processes in critical events [28]. As a next step, the usefulness and the correctness of the

Fig. 4. Cognitive insights to influence the adaptability of CPSs



resulting operational definition of MMs for our specific application has to be validated based on captured instances of MMs. Since the MM concept has been studied for about seven decades in psychology, while it is relatively new within design engineering, we will apply the methods from the cognitive psychology for this. A commonly applied method for capturing MM instances in psychology is through interviews.
Subsequently, predictive power will be inferred from the captured instances by exposing them to selected events and monitoring the effects on human reasoning and behaviour. These data will be analysed to find cause-effect relationships. From these discoveries, theories will be derived describing the behaviour of MMs for specific events. Both for validation and evaluation of the operational construct of an MM for our specific objectives, and for the elaboration towards predictive functionality based on new theoretical insights, we will reach a point where we either have to become an expert in the field or find close cooperation with cognitive psychologists to integrate their knowledge in our work. To verify the obtained results and to elaborate on the new insights, the expertise of a cognitive psychologist is expected to add more value than can be achieved through solely reading and applying published results.

4 Discussion and conclusions

The practical application potential of knowledge from cognitive sciences to design engineering problems is still largely unexplored. In the paper we discuss two directions of transdisciplinary design/research in this area that we are currently exploring. In the first one we aim to deploy cognitive architectures (CAs) in evaluating designs of safety-critical CPSs and minimize harmful cognitive effects, and in the second one we aim to consider the concept of mental models (MMs) as a carrier to harmonize the information exchange with systems to the user's expectations and reasoning patterns. We expect that adoption of such approaches in CPS design will eventually result in optimally symbiotic relations between humans and the increasingly complex systems around them. Regarding the two, seemingly closely related, directions of research and their transdisciplinarity, we would like to conclude with two observations. One concerns the recognition of 'cognitive science' as one monolithic discipline, the other concerns the recognition of 'experts' from another field in general.
An obvious future step in our work would be to expand the scope of transdisciplinarity and combine MMs and CAs in one design-support approach. A possible challenge in such a cooperation is that it may necessitate cooperation between disjunct research communities within cognitive science, who even might represent diametrically different viewpoints on how the human brain works and how it should be investigated.
Regarding the decision to involve *experts* from other disciplines, the need arises to reflect on the distinction between experts and non-experts. Alexander [2] states that characterizations of expertise were traditionally based on sharp contrasts between experts and neophytes, but that in fact, subtle and significant transformations occur between those extremes. Ahmed et al. [1] and Sonnentag [26] tried to express the distinction between non-expert and expert in years of experience in a field. Based on interviews, Ahmed et al. found that, in the field of engineering design, someone is

considered an expert after 5-15 years of relevant experience, while Sonnentag argued that expertise in software engineering requires at least ten years. Apparently, there is no sharp definition of ‘expert’ that can be used to decide whether a partner contributing knowledge from another discipline is an expert and consequently makes a project a TD project.

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