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Design of Information-Intensive Systems Involving Cognitive Aspects: An Emerging Opportunity for Transdisciplinary Cooperation

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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. With the objective to reduce the risk of unwanted cognitive effects and to realize a more symbiotic relationship between users and systems, we show how two model-based theories from cognitive science, i.e., cognitive architectures and mental models, can be deployed in the design of these 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 · Information-intensive systems · Mental models · Cognitive architectures · Transdisciplinary cooperation

1 Introduction

Information-intensive systems (IISs) have been defined as systems where the use and production of information is either a major function or a major component of the control of the process. Such a system usually has as its components hardware and human beings, using software and procedures, respectively (Yamamoto et al. 1982). These systems have been part of our everyday lives for decades, as they include telecommunications, the electric grid, banking and financial services, manufacturing, surface transportation, petroleum delivery and emergency services (Jones

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2000). IISs increasingly take the form of their current manifestations known as the internet of things (Horváth and Gerritsen (2012), meta-products (Huisman et al. 2011) and cyber-physical systems Lee 2006). They are often deployed in product-service systems (Boehm and Thomas 2013). As a consequence of their complexity, IIS development 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 disciplines involved in designing the first generations of IISs were, among others, information and communication technology (ICT), industrial design engineering and mechanical engineering. Integrating cognitive psychology issues will be a key challenge in developing the next generations of IIS.

For various types of IISs it has already been argued that they require a transdisciplinary approach (Huisman et al. 2011), or inter-, multi- and transdisciplinary at the same time (Horváth and Gerritsen 2012). In the next section, we will present our interpretation of what 'transdisciplinary' is, considering the supporting literature and the context of IISs, as well as the distinction between trans-, multi-, interdisciplinary etc. Then, in Sect. 3 we elaborate on cognitive aspects of interacting with and designing IISs. We have identified these as an opportunity to set out directions for transdisciplinary cooperation, two of which are further elaborated in Sects. 4 and 5, respectively. The chapter wraps up with the discussion and conclusions in Sect. 6.

2 Transdisciplinarity in the Context of Developing IISs

According to Horváth and Gerritsen who discuss cyber-physical systems (CPSs) in Horváth and Gerritsen (2012), *interdisciplinarity* involves two knowledge domains (for CPSs: the cyber and physical domains), *multidisciplinarity* involves more than two knowledge domains (e.g. biology, engineering and computer science), 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' (Pohl 2000).

Generalizing these statements regarding what the various 'disciplinarities' mean in terms of cooperation between disciplines, we have concluded that they describe different types of professional activities in two dimensions, one dimension being that of the different domains (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 (Max-Neef 2005). Regarding cooperation, Wickson et al. (2006) signify 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 about crossing disciplinary borders, we can learn from literature concerning the crossing of geological borders by companies, where the analogous terms inter-, multi- and transnational are commonly used. In that context, the set of definitions by Bartlett (1986) is often cited. In our context, the *differences in handling knowledge* that he 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: ***Monodisciplinarity*** (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 purely 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 cooperation 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 pill dispenser for consumers (who may be also patients) in cooperation with a medical company. In the case of interdisciplinary design, the medical company acts as the principal and 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. Figure 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 cooperation at multiple, or even *all* (Max-Neef 2005), levels in two or more value chains. This is shown in Fig. 2, where cooperation should span at least one of the diagonal arrows or two of the horizontal arrows. In addition transdisciplinary (TD) activities may be inter-/multi-/intradisciplinary 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 cooperation 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 cooperation, we also consider the level of *maturity* of the connections between distinct disciplines relevant in characterising transdisciplinarity. Typical TD

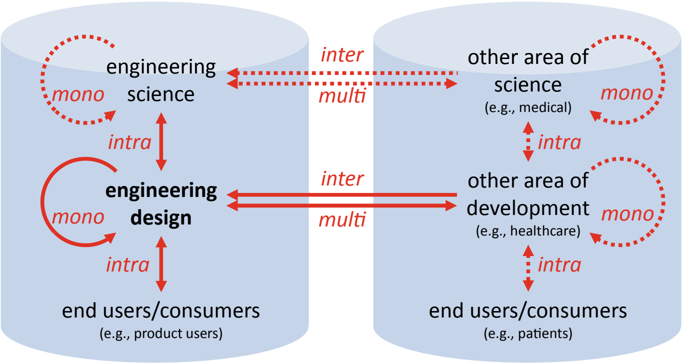

Fig. 1 Illustration of the meanings of *monodisciplinary, interdisciplinary, multidisciplinary* and *intradisciplinary*, reasoning from the field of engineering design

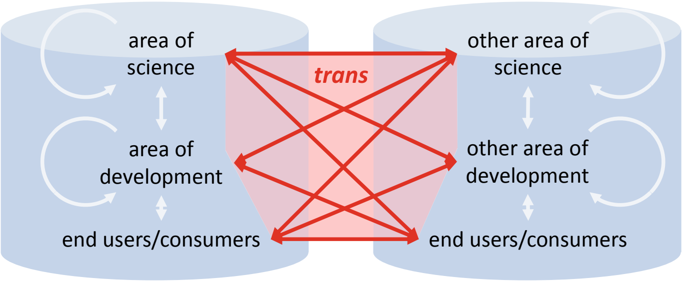

Fig. 2 Various forms of transdisciplinarity (elaborating on Fig. 1)

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 a simplified view on the subject matter. Firstly, disciplines can be considered at various levels of abstraction. Therefore, the scope of 'disciplinarities' also depends on the observer's level of abstraction. 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* 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. And, as another contribution in this book shows, in urban infrastructure design, also the activities performed by stakeholders such as regulatory bodies and authorities can be recognized as parts of the value chain (Leblanc 2014). 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.

3 Cognitive Aspects and Issues of IISs

This section elaborates on one typical characteristic of IISs that we think requires a TD approach, namely that, in the way they are designed and the ways in which they function, IISs address issues of *human cognition* as well as *artificial cognition.* IISs will increase the level of communication and knowledge conversion technologies built into consumer products and systems. On the one hand IISs can take over particular cognitive tasks from users. Therefore, IIS designers will have to allocate cognitive tasks between user and IIS, and to design outputs of IISs to be relevant for users.

On the other hand, IISs are part of the information society that produces ever-increasing amounts of available information, both valuable and useless. It means that besides *reducing* cognitive task loads, IISs may also confront users with *increased* amounts of information. The increase may negatively influence use comfort, and cause perceptual and/or cognitive overload in demanding situations. In addition, it is expected that, since they offer functionalities that cannot be realized with conventional technology, IISs will increasingly be deployed in safety–critical situations (Karnouskos 2011). From conventional safety–critical systems, such as nuclear plants, it is known that their evaluation involves identification of rarely occurring scenarios, e.g., once in 1,000 years (Beckjord et al. 1993). In many circumstances where IIS will play an increasingly important role, such as car driving, air traffic and medical care (Baheti and Gill 2011; Lee and Sokolsky 2010; Work et al. 2008), we also have to consider infrequent scenarios (e.g. likelihood once in 500 years per driver/pilot/physician) in risk assessment. This is only possible by comprehensively understanding human cognitive behaviours under varying situations including emergency or stressful scenarios (Poovendran 2010).

We believe that this increased understanding will eventually enable designers to realize cognitive symbiosis between IISs and humans, from which not only safety–critical IIS but also IIS supporting everyday life, will benefit—for instance by increasing user comfort and satisfaction. Achieving symbiosis is expected to be more important for IIS intensively interacting with humans, and arguably less for autonomous IIS acting without any human intervention. The desired symbiosis requires knowledge from cognitive science, and development of design tools in cooperation with cognitive scientists. In addition it is likely to also require involvement of end users, both in research and in design activities. It is expected that, because the cooperation spans across the knowledge value chain *and* various domains, the resulting TD cooperation will pose several challenges to the stakeholders involved. It means 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 chapter we will briefly discuss two directions of research in which we aim to study how knowledge from the cognitive sciences can be used in ISS development processes, addressing the above issues at two levels. The first one, introduced in Sect. 4, 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 IIS 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 Sect. 5, addresses the issues at a higher level in order to support the early stages of designing IISs. 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 Figs. 1 and 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 Sects. 4 and 5 we will mostly focus on explaining the cognitive-science involvement.

4 Simulating Cognitive Loads and Processing Times

The first research direction concerns a plan conceptualized together with cognitive scientists to develop an approach for co-simulating human mental processes and models of products and systems. The goal is to evaluate IISs 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 IISs without humans in the loop by using a *cognitive architecture* (CA) as a model of human information processing and decision-making. One project concerns simulation of centralised pound-lock control (PLC) rooms, to be operationalised by our government agency of public works from 2014 onwards. The second category of IISs that we consider for conceptualization and study is emergency response systems (ERSs) in buildings. ERSs currently involve several systems and devices, some of which operate connectedly to facilitate a variety of situations, including fire detection, medical assistance, communication with firefighters/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. Systems with some of these technologies have already been prototyped, but so far mostly focusing on victim monitoring by medics at large-scale disaster sites (e.g. Gao et al. 2008). We expect additional challenges when dealing with, for instance, non-expert volunteers, evacuation of buildings and isolated but more frequently occurring incidents and drills.

Both the PLC system and ERSs nicely illustrate the potential of our approach for IIS designers because they are safety–critical, and the IIS 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 PLC 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 'zipper-wise operation' increases the operators' multitasking load. In exceptional cases, cognitive processing errors by operators may lead to severe accidents or even disasters (colliding ships, flooding). Likewise, emergency response workers 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 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 use an interactive simulator for testing all combinations of factors and sequences of occurrence. 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, etc. (Salvucci et al. 2009)—we expect to run the simulations much faster than real-time, so that even rare critical situations can be revealed (Vegte and Moes 2012).

CAs are blueprints of cognition based on findings from brain science. Figure 3 shows ACT-R's modules and the identified corresponding areas in the human brain (Anderson et al. 2004). The *external world* block corresponds to everything outside the human. In our pond lock example it would comprise the operation interface, the

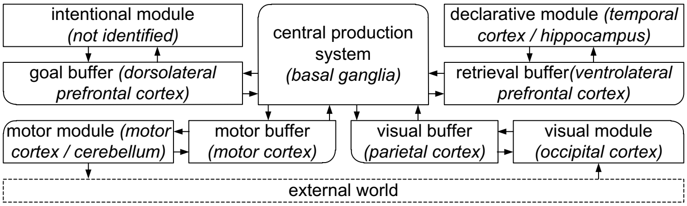

Fig. 3 Modules of ACT-R and corresponding cortical regions (*in italics*). Adapted from Anderson et al. (2004)

locks themselves with related 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 describing information-processing behaviour related to specific subtasks (Patterson et al. 2013). For common subtasks, LISP routines are readily available; for others, laboratory studies with human subjects have to be conducted 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 mainly used by cognitive scientists 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 Anderson et al. 1997), through interactions with software via mouse, keyboard and monitor (Byrne 2005), to specific tasks in aviation (Byrne and Kirlik 2005) and car driving (Salvucci 2006)—they have not yet been applied in interaction with complex multi-faceted external world models, despite obvious potential benefits. A possible explanation is that, on the one hand designers are not aware that simulation of mental processes is actually possible, and that on the other hand cognitive scientists come from a research tradition of controlled experiments that benefit from simple external worlds. To promote pioneering in TD projects, we therefore have to facilitate designers in utilising research efforts that can contribute to their work, and find ways to make researchers benefit from practical applications. In the case of PLC simulations, this might involve developing validation methods for outcomes like 'once in 1,000 years, a cognitive operator error will cause 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.

5 Realizing Awareness of Mental Models in IISs

The second direction of research focuses on *informing systems* and aims to find novel means to inform users and to find new symbiotic relations between human and systems, based on which designers can be supported in the early stages of IIS development. In cognitive psychology the internal representation that people hold

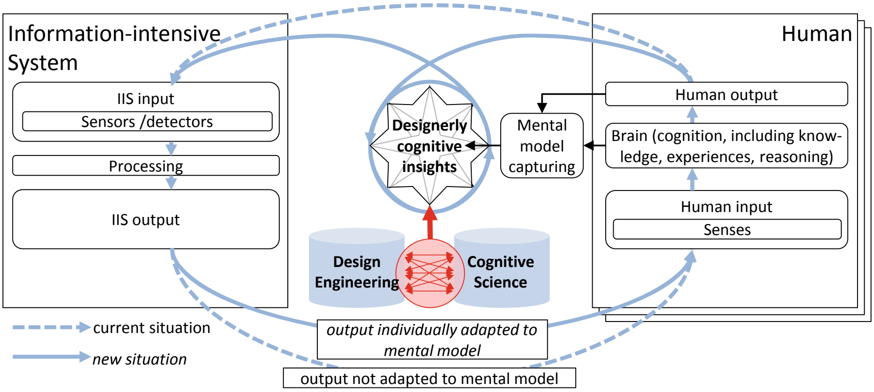

Fig. 4 Cognitive insights to influence the adaptability of IISs

of an external reality that allows them to explain, interact, and predict that reality is called a mental model (MM). MMs have been identified as a basis of human reasoning (Johnson-Laird 2010). 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 IISs, and to provide guidelines for designers based on these insights. The project will therefore produce a predictive theory and additionally formulate its affordances for the design process. In Fig. 4 it is shown that human output can be directly detected by the system. Currently this is detected through for example motion detection, id-tags or smartphone detection. In the future desired situation the cognitive implications in the human output will be interpreted with the obtained designerly cognitive insights enabling the system to adapt its output to the cognitive capabilities of an individual user in a specific situation. It may give specifically the information that will help to take a right decision to react.

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 phase 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 IISs and correct regarding its psychological fundamentals, the disciplines of design engineering and cognitive psychology have to be fused.

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. 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 (Deurzen et al. 2013). As a next step, the usefulness and the correctness of the 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. A commonly applied method for capturing MM instances in psychology is through interviews. To obtain the designerly cognitive insights, two aspects of the behaviour of mental models are studied. A first element of the behaviour is whether inertia occurs when switching from one mental model to another. For instance will there be a different reaction on the same unexpected situation if the person was reading an exciting book as when he was playing football? A challenge for this study is to cope with the irreversibility of perceptions that occur even in experimental set-ups. A second contribution to the designerly insights will be the exploration and development of a method to identify inadequacies in a person's knowledge and experience. In cognitive psychology it is commonly accepted that mental models are inaccurate and incomplete (Sonnentag 1998). Gained insights in identifying the gaps and faults in a MM will indicate ways to "repair or improve the MM" which means to better inform people. Subsequently, a study to effectively address the insufficiencies in a mental model will constitute the bridge towards guidelines for designers to develop IISs with adaptive capabilities on the user's cognition. These aimed guidelines for addressing the gaps and faults in a MM will include the contents, the senses to address and the effect of the amplitude of the message, being e.g. the volume of aural information or the pressure level of haptic information.

Hence 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 fuse the knowledge and methods. 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.

6 Discussion and Conclusions

In this chapter we discuss transdisciplinary cooperation between design and research in the context of IISs. We started out from setting transdisciplinarity apart from (in particular) multidisciplinarity and interdisciplinarity, which may have led to a somewhat stricter interpretation of transdisciplinarity than has been proposed in other contributions to this book. However, our definition can be used in accordance with most of the other definitions and descriptions that have been brought forward during the workshop and in this book, such as the often-cited assertions that transdisciplinarity should integrate beyond the boundaries of the contributing disciplines and that it is holistic [cf., Fernandez-Orviz (2014), Gericke (2014)]. The definitions appear to agree that transdisciplinarity involves more mutual commitment between disciplines than multidisciplinarity or interdisciplinarity.

We are currently exploring two directions of transdisciplinary design/research in the interfacing area between engineering and cognitive science. The practical application potential of knowledge from cognitive sciences to design engineering problems is still largely unexplored. The first presented research direction aims to deploy cognitive architectures (CAs) in evaluating designs of safety–critical IISs 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 IIS 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 transdisciplinary scope 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 (2003) 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. (2005) and Sonnentag (1998) express the distinction between non-expert and expert in years of experience. 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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