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Review

Integrating cognitive load theory and concepts of human–computer interaction

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ABSTRACT

With the continually increasing complexity of e-learning environments, there is a need for integrating concepts of cognitive load theory (CLT) with concepts of human–computer interaction (HCI). Basic concepts of both fields were reviewed and contrasted. A literature review was conducted within the literature database "The Guide to Computing Literature," searching for "cognitive load theory" and "Sweller." Sixty-five publications contained "cognitive load" in their titles or abstracts. Each publication was checked to see whether it contained the concepts of intrinsic, extraneous, or germane cognitive load. The review showed that CLT concepts have been adopted in HCI. However, the concept of germane cognitive load has attracted less attention up to the present time. Two conceptual models are proposed. The first model divides extraneous cognitive load into load induced by the instructional design and load caused by software usage. The model clarifies the focus of traditional usability principles and of existing instructional design principles derived from CLT. The second model fits CLT concepts into the basic components of user-centered design. The concept of germane cognitive load illustrates that an increase of cognitive load can be desirable when designing e-learning environments. Areas for future interdisciplinary research are sketched.

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1. Introduction

Since its origination in the 1980s, cognitive load theory (CLT) has become an acknowledged and broadly applied theory within the field of instruction and learning (Schnotz & Kürschner, 2007; Van Merriënboer & Sweller, 2005). The first decade of CLT was focused by research on instructional methods for decreasing extraneous cognitive load that is caused by a suboptimal design of learning tasks. Since then, the focus of research has developed in several directions, such as the role of the level of expertise of learners with regard to instructional principles, or methods to foster germane cognitive load required for relevant learning processes (for an overview, see Ayres & Van Gog, 2009; Van Merriënboer, Kester, & Paas, 2006; Van Merriënboer & Sweller, 2005). This paper aims to explicitly point out a further direction, namely, the application of CLT for the design of complex electronic learning environments. CLT research has shifted from studying paper-based learning tasks to studying web-based learning (Van Merriënboer & Ayres, 2005) and has expanded to apply CLT principles in complex e-learning scenarios both for individual and group learning (Kester, Kirschner, & Corbalan, 2007). A specific case within such scenarios is the application of software tools that allow learners to create media in their learning process (Kiili, 2006).

The task to assure an optimization of cognitive load in traditional CLT research has been the responsibility of instructional design experts. They design learning materials in a first step that are used by learners in a second step. If learners actively take part in the media creation process, or if learners have the opportunity to alter the presentation of learning materials, this responsibility slips to a certain extent out of the hands of instructional design experts. Hence, we argue that the optimization of cognitive load needs to be taken into account in the design of the software used by learners. Recent research on task selection for individual learners (Corbalan, Kester, & Van Merriënboer, 2009) or on cognitive load in collaborative learning (Kirschner, Paas, & Kirschner, 2008, 2009a, 2009b) has sketched directions for how this could be achieved.

Given that CLT continues to move in this direction, it will have to deal with a set of issues that are related to software design and usage. These issues are traditionally dealt with in the field of human–computer interaction (HCI). The present paper therefore is concerned with the following questions: (a) Are concepts of CLT and concepts of HCI compatible? (b)To what extent have the concepts and principles of CLT been assimilated by HCI theories and approaches? (c) Can both areas profit from each other?

To do so, first, the basic assumptions of CLT are described. In a next step, the historical development of the HCI discipline as well as important concepts and methodologies are outlined and contrasted with CLT. Furthermore, the application of CLT concepts within HCI is reviewed by conducting a literature search for CLT-related publications within HCI literature databases. Finally, two models are presented that integrate basic concepts of CLT and HCI. The models are used to sketch areas of possible interdisciplinary research.

2. Cognitive load theory and its basic assumptions

In the following, the basic assumptions and concepts of CLT will be outlined (for a detailed description, see Sweller, 2005a; Sweller & Chandler, 1994; Sweller, Van Merriënboer, & Paas, 1998). CLT is based upon the notion of a limited working memory capacity (cf. Baddeley, 1976; Miller, 1956) and a vast long-term memory capacity. Working memory is constituted of partially independent processors that are related to different sensory channels. Baddeley (1976, 1992) assumed a "phonological loop" for auditory information and a "visuo-spatial sketchpad" for visual information. Under specific circumstances, working memory capacity can be increased by involving several sensory channels at a time, rather than only one channel. Any conscious cognitive activity requires working memory capacity. It is the basic assertion of CLT that any instructional design needs to take the limitations of working memory into account in order to prevent an overload of working memory capacity and hence a deterioration of learning (Sweller, 2005a).

CLT refers to schema theory (Chi, Glaser, & Rees, 1982) in order to model learning. According to this theory, knowledge in long-term memory is stored in mental schemata. Learning is due to the construction of schemata. By integrating lower-level schemata, complex higher-order schemata are constructed that allow skilled performance. A schema can be treated as a single element in working memory and hence functions to overcome working memory limitations. Furthermore, through schema automation, information can be processed without demands on working memory (Shiffrin & Schneider, 1977).

CLT distinguishes between three types of cognitive load that occur in working memory during learning. The first, intrinsic cognitive load, is defined by the intrinsic complexity of information that is to be learned. It depends on the interactivity of elements. Learning vocabulary is an example of low element interactivity, as each word can be learned independently. Learning how to build sentences in a foreign language, on the contrary, is an example of high element interactivity as it requires an understanding of different parts of speech and their sequencing. The intrinsic load of a task can only be defined in relation to the level of expertise of a learner (Bannert, 2002; Sweller et al., 1998).

The second type of cognitive load, extraneous cognitive load, is caused by an inappropriate presentation of the learning material or by requiring students to perform activities that are irrelevant to learning. For example, having to integrate information from spatially separate sources of information increases extraneous cognitive load; information from one source needs to be maintained in working memory in order to integrate it with the information from the other source (Ayres & Sweller, 2005).

The final type of cognitive load, germane cognitive load, results from active schema construction processes and is thus beneficial for learning. Originally, CLT differed only between intrinsic and extraneous cognitive load. Germane cognitive load was introduced after Paas and Van Merriënboer (1994; see also Sweller et al., 1998) had found that the variation of worked example types increases cognitive load, but at the same time supports the construction of schemata.

Extraneous, intrinsic, and germane cognitive load are modeled to be additive (Paas, Tuovinen, Tabbers, & Van Gerven, 2003). A reduction of extraneous cognitive load frees working memory capacity that can be used for germane learning processes. However, such an effect is only visible in learning settings with a high intrinsic cognitive load. If intrinsic load is low, learning can be successful despite a high extraneous load. The total amount of cognitive load needs to remain within the total cognitive capacity (Van Merriënboer & Sweller, 2005).

2.1. Criticism on original definitions of CLT concepts

Recently, the conceptualization of the three types of cognitive load has been criticized. De Jong (2009) pointed out that intrinsic and germane load belong to two different ontological categories: Intrinsic load refers to the complexity of the material, whereas germane load refers to cognitive processes. Schnotz and Kürschner (2007) offered refined definitions of the three types of cognitive load and pointed out connections between them: Intrinsic load is modeled as cognitive processes related to the performance of a learning task, with understanding as a specific type of performance. According to Schnotz and Kürschner, the performance of the learning task can induce learning, but does not necessarily do so. Germane load, according to their definition, is related to cognitive processes that go beyond simple task performance. According to Schnotz and Kürschner, these germane processes are fostered by activities such as "conscious application of learning strategies (...), conscious search for patterns in the learning material on order to deliberately abstract cognitive schemata (...), restructuring of problem representations in order to solve a task more easily (...), meta-cognitive processes that monitor cognition and learning" (Schnotz & Kürschner, 2007, p. 496).

By referring to implicit knowledge that can be acquired without conscious cognitive activities requiring working memory capacity, Schnotz and Kürschner assumed that germane cognitive load was "no longer a prerequisite of any kind of learning (...) Learning can occur also without germane load, but germane load can further enhance learning" (p. 497).

Furthermore, Schnotz and Kürschner argued that intrinsic and germane cognitive load are dependent in such a way that germane cognitive load can be hindered by an intrinsic load that is either too high or too low, while an intrinsic load adjusted to the learner's expertise allows for the maximum germane load. With regard to optimally adjusting the task complexity to a learner's level of expertise, Schnotz and Kürschner referred to Vygotsky's zone of proximal development (Vygotski, 1963). They thus pointed out a connection between intrinsic load and extraneous load such that extraneous load can be caused by a task complexity that is either too high or too low, according to their definition.

De Jong (2009) and Schnotz and Kürschner (2007) pointed out very plausibly that extraneous, intrinsic, and germane load may be interrelated beyond simple addition. However, Schnotz and Kürschner's definition of intrinsic and germane cognitive load also raised new issues: For example, it may be difficult to exactly distinguish between intrinsic and germane load: Where does simple task performance or understanding end, and where do germane cognitive processes begin? Furthermore, it can be questioned whether it is correct that implicit learning does not require working memory capacity: For instance, Reber and Kotovsky (1997) showed that implicit learning also depends on working memory capacity. One could hence argue that implicit learning also requires germane cognitive processes and that the essential difference between implicit and explicit learning is rather that implicit learning is subconscious (cf. Schnotz & Kürschner, 2007).

If we retain the definitions of intrinsic cognitive load as related to task complexity and germane cognitive load as related to schema acquisition, we avoid these issues. Assuming that learning requires some form of germane cognitive load still allows for modeling the connections between the three types of cognitive load as Schnotz and Kürschner (2007) proposed: Intrinsic cognitive load defined as task complexity can provide the potential for germane cognitive load, and a task complexity that is too high or too low may cause extraneous cognitive load.

2.2. Instructional design principles derived from CLT

CLT research has developed a range of instructional design guidelines or effects that are intended to influence the three types of cognitive load (Van Merriënboer & Sweller, 2005).

2.2.1. Principles to reduce extraneous load

In the first years of CLT research, the focus was on possible methods for reducing extraneous cognitive load (Schnotz & Kürschner, 2007; Van Merriënboer & Ayres, 2005). The worked example effect, the split-attention effect, the modality effect, and the redundancy effect will be described in the following.

According to the worked example effect, novice learners profit from studying worked examples rather than solving conventional problems, as they can focus on problem states and useful solution steps rather than using inefficient strategies that place heavy demands on working memory (Sweller, 2006; Sweller et al., 1998).

The split-attention effect indicates that multiple sources of visual information should be presented in an integrated way if all information sources are a prerequisite for understanding. If the sources are displayed in a separate format, the information needs to be integrated mentally, which induces a heavy load on working memory (Ayres & Sweller, 2005; Sweller et al., 1998).

The modality effect also occurs when multiple sources of information are required for understanding. Extraneous load with regard to the visual modality can be reduced by presenting verbal information in spoken rather than written form, thus using the auditory processor in working memory (Low & Sweller, 2005).

The redundancy effect implies that presenting multiple sources of information that simply reiterate the same information in a different form should be avoided when one information source is sufficient for understanding. Having to integrate the redundant information induces unnecessary memory load (Sweller, 2005b).

When comparing these principles, it appears that they differ with regard to the extent to which they alter information processing in working memory. While the split-attention principle simply prevents additional information from having to be kept in working memory, the worked-example principle changes the way information is processed in a much more profound way. This is consistent with the suggestion of Schnotz and Kürschner (2007) that extraneous load can be caused by additional information that has to be kept in working memory, and by a complexity of the learning material that is too high in the case of problem solving.

2.2.2. Principles to foster germane load

Next, instructional design methods were found to increase germane cognitive load, specifically with regard to learning with worked examples. Paas and Van Merriënboer (1994; see also Sweller et al., 1998) introduced the variability effect, according to which the variability of tasks increases cognitive load, but at the same time improves learning outcomes. Prompting students to link concrete example information to more abstract information for each problem category also supports schema acquisition (Atkinson, Renkl, & Merrill, 2003; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Gerjets, Scheiter, & Schuh, 2008). Gerjets et al. (2008) explicitly supported comparisons across example categories to foster germane learning processes. Other research has been concerned with self-explanation strategies to foster germane cognitive load (Stark, Mandl, Gruber, Renkl, & Sweller, 2002; Van Merriënboer & Sweller, 2005).

Furthermore, providing learners with learner control over task selection seems to be supportive of germane learning processes (Corbalan et al., 2009; Van Merriënboer, Schuurman, De Croock, & Paas, 2002).

2.2.3. Principles to adjust intrinsic load

With regard to very complex learning content, attempts were made to find situations in which it was possible to adjust intrinsic cognitive load. Pollock, Chandler, and Sweller (2002) presented information in isolated elements that could be processed serially by learners as a first step. In a second step, all elements of information were presented at once, including connections between elements. This approach was more beneficial to learning outcomes when compared to presenting all information at once in both phases.

2.2.4. The role of learner characteristics

A learner characteristic that has played a large role in CLT research is the level of expertise of the learner (Ayres & Van Gog, 2009; Kalyuga, Ayres, Chandler, & Sweller, 2003). According to the expertise-reversal effect, specific instructional formats can be beneficial for novices, but the same formats lose or even reverse their effect for more experienced learners (Kalyuga et al., 2003; Schnotz & Kürschner, 2007). The expertise-reversal effect has been demonstrated with respect to the split-attention effect, the modality effect, and the worked example effect (Kalyuga et al., 2003).

Seufert, Schütze, and Brünken (2009) researched the impact of individual memory strategic skills and working memory capacity on the modality effect. Moderated by the integration demand of a task, only learners with less developed strategic memory skills (high integration demand) or lower working memory capacity (low integration demand) profited from the presentation of verbal information in an auditory format rather than visually.

Recently, motivation has been brought into focus as another factor that may influence cognitive load (Paas, Tuovinen, Van Merriënboer, & Darabi, 2005; Schnotz, Fries, & Horz, 2009). Motivation, as a determinant of the intensity, direction, and continuance of behavior is considered as a fundamental condition for the relevance of CLT considerations (Schnotz et al., 2009). The beneficial effects of providing learners with learner control (Corbalan et al., 2009; Van Merriënboer et al., 2002) could be explained by increasing the motivation of learners to invest mental effort. The prior interest of learners with regard to a topic may also influence this motivation (Schnotz et al., 2009).

3. Human–computer interaction as a field of research

Having presented the basic assumptions and concepts of CLT, the following sections will introduce HCI as a field of research. HCI involves different scientific disciplines and deals with "the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" (Hewett et al., 1996, p. 5). It emerged as a distinct research discipline in the late 1970s and early 1980s when monitors and workstations became available and opened up the use of computers to nonengineers (Grudin, 1990; Preece, Sharp, & Rogers, 2002). Existing knowledge concerning ergonomics and human factors was applied to design interaction devices with regard to perceptual or motor issues. Later on, expertise from cognitive psychology was applied to develop command languages or menu designs. By the mid 1980s, the range of users was broadened further. Using computers for educational purposes became a focus with regard to interactive learning environments or training simulators.

In the 1990s, network technology and mobile devices broadened the scope of research beyond the individual user and personal computers. The goal was then to design interactive systems for individuals and groups in various application areas: Work, education, or entertainment, at home or in a mobile context. Research in this area involved experts from other fields such as sociology and anthropology (Rogers, 2004).

Major HCI research areas comprise theories and models of human behavior when interacting with information technology, general or more specific guidelines or heuristics for the design and evaluation of information technology, methods for the user-centered development of information technology, and the development of new interaction paradigms and technologies (cf. Preece et al., 2002).

3.1. Models of human cognition in HCI

The theories applied to model human cognition in CLT also influenced a large part of HCI research and major concepts developed in the 1980s (cf. Rogers, 2004). The fact that human working memory can hold only a limited number of items at a certain time (Baddeley, 1992; Miller, 1956) is common knowledge in user-interface design (Rogers, 2004). Atkinson and Shiffrin's (1968) model of sensory memory, short-term memory, and long-term memory, and Baddeley's (1976) component model of working memory influenced Card, Newell, and Moran's (1983) human processor model of interacting with a computer. A major goal in interaction design derived from these models was to decrease cognitive load for users as much as possible (Mandel, 1997; Preece et al., 2002).

Specific application areas have made use of further cognitive theories. Thus, researches have derived recommendations for the design of web browsers from theories of attention and decision making (Chen, Wang, Proctor, & Salvendy, 1997). Furthermore, with the development of distributed and mobile devices, concepts from distributed cognition and external cognition have been applied. These approaches study cognition in context or "in the wild," with a central goal of understanding how environmental structures can support cognition and specifically reduce memory load (Preece et al., 2002; Rogers, 2004).

3.2. Usability

Usability is one of the central concepts of HCI (Chalmers, 2003; Sharp, Rogers, & Preece, 2007). According to the International Organization for Standardization, usability is defined as the extent to which a user can fulfill a task using a tool effectively, efficiently, and with satisfaction (ISO 9241-11, 1998). The level of the usability of a tool or application can be defined only in the context of its specific users and the specific tasks that are to be accomplished. Hence, designing highly usable software applications requires an in-depth understanding of the specific users and their tasks (Mandel, 1997; Preece et al., 2002).

Various usability guidelines of different specificity have been developed, ranging from high-level usability goals to very specific design principles (Nielsen, 1994a; Sharp et al., 2007; Shneiderman & Plaisant, 2004). For example, Nielsen (1994a) listed five usability goals a system should achieve: learnability, memorability, efficiency, low error rate, as well as satisfaction. With regard to learnability, a system should allow novice users to reach a suitable level of proficiency within a short amount of time. Memorability refers to the ease with which a system can be reused after it has already been learned. It is specifically important with regard to systems that are infrequently used. The efficiency of use concerns the effort a user has to invest to complete a specific task. Systems should minimize errors induced by incorrect user actions, and if such errors occur, it should be easy for the user to recover from them. Satisfaction concerns how pleasant it is for a user to use a system, which may be especially important for systems in a nonwork domain.

An example of a specific design principle that can be implemented to prevent errors is a function that enables the user to select an option from a menu rather than having the user typewrite a command because spelling errors can be prevented in this way (Nielsen, 1994a; Shneiderman, 1998).

Regardless of the specificity of the guidelines, a recurring usability goal is to reduce memory load for users (Van Nimwegen, Van Oostendorp, Burgos, & Koper, 2006). Methods for reducing memory load consist of having users focus on recognition rather than on recall, for example, by externalizing information; preventing users from having to remember information from one screen to the other; using generic commands such as copy and paste; keeping displays simple and clear, for example, by applying Gestalt laws; offering functionalities only in the context in which they are needed; and training users when complex interactions are required (Mandel, 1997; Nielsen, 1994a; Shneiderman, 1998; Van Nimwegen et al., 2006).

3.3. User experience goals

With the development of computer applications beyond the work context, further concerns besides usability goals came up, such as the degree to which a system was considered enjoyable, motivating, aesthetically pleasing, or supportive in creativity. Within the research on user experience goals, the claim was made that in the context of entertainment it might be interesting to build systems that are less efficient to use or more difficult to learn, thus opposing the traditional usability goals, but influencing motivation or joy (Preece et al., 2002).

Usability goals and user experience goals are not entirely distinct from each other since usability impacts the quality of the user experience, and components of the user experience may also influence the perception of the usability of a system (Sharp et al., 2007). With regard to the latter, Kurosu and Kashimura (1995) and Tractinsky (1997) found that ATM machines with higher aesthetic attractiveness but equivalent functions were perceived as more usable than ATM machines with lower aesthetic attractiveness.

3.4. HCI and learning

Learning processes play a role in HCI with regard to two major aspects (Sharp et al., 2007). One general aspect is that novice users have to learn how to use a computer system in order to complete specific tasks (Nielsen, 1994a). The second aspect concerns educational software that aims to support knowledge and skill acquisition in various domains.

With regard to learning how to use a computer system, Carroll (1990) developed a training-wheels approach: For novice users, only basic functions are available, but with increasing expertise, the possible functions are extended. Similarly, context-sensitive systems can hide or disable inappropriate functions according to the specific tasks at hand, thus minimizing the problem space (Van Nimwegen et al., 2006; Van Oostendorp & De Mul, 1999).

With regard to educational software, different researchers have dealt with the role of usability in an educational context. For example, Tselios, Avouris, and Dimitracopoulou (2001) applied traditional usability measures to rate the usability of one of two online learning systems. Students had to perform a test after using one of the learning systems for 15 min. The group of students using the system that was rated most usable showed significantly better learning outcomes. Researchers have claimed that the concept of usability in the field of educational computing has to be adapted to pedagogical approaches and theories of learning (Hornbæk, 2006; Mayes & Fowler, 1999; Squires & Preece, 1999). Tselios, Avouris, and Komis (2008) pointed out that the difference between learning technology and technology used as a productivity tool is that learning technology should not simply support the efficient execution of a task. In specific cases, increased usability could have a negative impact on learning, since executing a task efficiently may prevent essential learning processes.

There are two main research directions concerning the user-centered design of educational software applications: The first one is concerned with the evaluation of e-learning applications (e.g., Ardito et al., 2004; Koohang, 2004; Mehlenbacher et al., 2005; Squires & Preece, 1999; Tselios et al., 2008; Zaharias & Poylymenakou, 2009), while the second research direction focuses on user-centered development methods for e-learning applications (Koohang & Du Plessis, 2004; Siozos, Palaigeorgiou, Triantafyllakos, & Despotakis, 2009). Koohang and Du Plessis (2004) concluded that existing user-centered design methods could potentially integrate a user-centered technology design and a learner-centered instructional design by bringing together a cross-functional design team including both software design specialists as well as educational design specialists.

Researchers have pointed out the important role of individual user characteristics with regard to designing and evaluating educational software (Chalmers, 2003; Sharp et al., 2007). For example, Chalmers (2003) named age, gender, the level of expertise with regard to the learning content, the level of expertise with regard to computer usage, affect and motivation as user characteristics that need to be considered.

4. Compatibility of CLT and HCI

CLT and the theories and concepts of HCI have shown similar historical developments. The same theories of cognition built the foundations of both CLT and HCI in the 1970s and 1980s. Both had a strong focus on the reduction of irrelevant cognitive load. With the concept of germane cognitive load, CLT included principles to foster germane learning processes, which consequently may lead to an increase in cognitive load. Similarly, in the context of designing applications for entertainment or education, research in HCI proposed that it might be beneficial to build applications that are less efficient or easy to use. However, this research direction in HCI is still new and opposes the traditional assumptions of HCI.

When comparing CLT instructional design principles to usability goals and principles, it appears that some CLT design principles have been applied in software design in similar ways. This applies specifically to the split-attention principle and the redundancy principle. In accordance with the split-attention principle, if a requirements analysis in software design indicates that different pieces of information are related to each other and are required for the completion of a task, the usability heuristic "The user should not have to remember information from one part of the dialogue to another" (Nielsen, 1994b), as well as the application of Gestalt laws (Chalmers, 2003; Chang, Dooley, & Tuovinen, 2002) would indicate that the pieces of information should be displayed in close spatial proximity. Also, in line with the redundancy principle, the usability heuristic "Every extra unit of information in a dialogue competes with the relevant units of information" (Nielsen, 1994a) would prevent information from being reiterated onscreen. Furthermore, theories and approaches from both CLT and HCI acknowledge the important role of learner characteristics, particularly of prior knowledge.

Other CLT principles appear to have no counterpart in HCI. This applies to the CLT principles designed to foster germane cognitive load, but also to some principles designed to reduce extraneous cognitive load, namely the worked-example principle and the modality principle. A reason for this may be that these principles are much more specific to learning processes.

4.1. Literature review on the application of CLT concepts in HCI

To investigate the extent to which CLT concepts have been explicitly applied in HCI research, a literature review was conducted. The "Guide to Computing Literature" is a database provided by the Association of Computing Machinery (ACM). It contains more than 1,200,000 citations from more than 3000 publishers (in November 2009), including books, journal articles, conference proceedings, doctoral dissertations, master's theses, and technical reports. The search was conducted with the terms "cognitive load theory" and "Sweller" (with regard to John Sweller as the father of CLT). Only results within books, journals, and conference proceedings were included; doctoral and master's theses were excluded.

Sixty-five of the remaining citations contained "cognitive load" in their title or abstract. The other articles cited publications by John Sweller or publications containing "cognitive load theory" in their title.

Table 1
List of CLT-related publications within the ACM literature database “The Guide to Computing Literature”.

Citations/topics	ICL (*n* = 43)	ECL (*n* = 61)	GCL (*n* = 36)
Design of computer-based instruction			
Alkhalifa (2008)	+	+	+
Amadieu et al. (2009)	+	+	+
Angeli, Valanides, and Kirschner (2009)	+	+	+
Austin (2009)	+	+	
Ayres et al. (2009)	+	+	+
Ayres and Van Gog (2009)	+	+	+
Caspersen and Bennedsen (2007)	+	+	+
Chang et al. (2006)		(+)	
Cierniak et al. (2009)	+	+	+
Clarebout and Elen (2005)		(+)	
Courtemanche et al. (2008)	+	+	+
DeStefano and LeFevre (2007)	+	+	+
Feinberg and Murphy (2000)	+	+	
Gray et al. (2007)	+	+	+
Guttormsen Schär and Kaiser (2006)	+	+	+
Hilbert and Renkl (2009)		+	+
Holzinger et al. (2009)	+	+	+
Homer, Plass, and Blake (2008)	+	+	+
Horz et al. (2009)	+	+	+
Ik-Park et al. (2009)	(+)	(+)	
Kalyuga (1997)		+	
Kalyuga (2008)	(+)	(+)	
Kalyuga (2008)	+	+	+
Kiili (2006)	+	+	+
Kirschner et al. (2009a, 2009b)	+	+	+
Korakakis et al. (2009)	+	+	+
Leutner et al. (2009)	+	+	+
Lim and Reiser (2006)	+	+	+
Lyons et al. (2006)		+	
Madrid et al. (2009)	+	+	+
Moos (2009)	+	+	+
Ngu and Rethinasamy (2006)	+	+	+
Oviatt (2006)	(+)	+	
Oviatt, Arthur, and Cohen (2006)	(+)	+	
Samaras et al. (2007)	+	+	+
Sawicka et al. (2008)	+	+	+
Schwonke et al. (2009)	+	+	+
Seufert et al. (2007)	+	+	+
Sinclair et al. (2004)		(+)	
Sweller (2008)	+	+	
Tudoreanu and Kraemer (2008)		(+)	
Tuovinen (2000)		+	
Wirth et al. (2009)	(+)	+	+
Wong et al. (2009)	+	+	+
Zumbach and Mohraz (2008)	+	+	+
Cognitive load measurement			
Hsu, Chang, Chuang, and Wu (2008)	(+)	(+)	
Khawaja, Ruiz, and Chen (2007)		(+)	
Khawaja, Ruiz, and Chen (2008)		(+)	
Razavi, Fleury, and Ghanbari (2008)			
Ruiz et al. (2007)			
Shi, Ruiz, Taib, Choi, and Chen (2007)		(+)	
Yin, Ruiz, Chen, and Khawaja (2007)		(+)	
Design of multimodal interfaces			
Elting, Zwickel, and Malaka (2002)		(+)	
Oviatt, Coulston, and Lunsford (2004)		(+)	
Ruiz, Taib and Chen (2006)		(+)	
Decision making			
Cao, Theune, and Nijholt (2009)			
Kim and Dey (2009)		(+)	
Schreiber (2009)			
Designing hypermedia/information search environments			
Chevalier and Kicka (2006)	+	+	(+)
Huang, Hong, and Eades (2006)		(+)	
Modeling of distributed cognitive load in groups			
Ang, Zaphiris, and Mahmood (2007)	+	+	+
Fan and Yen (2007)		(+)	
Game design			
Lawrence (2006)	+	+	+
Analysis methods for cognitive processes			

(*continued on next page*)

Table 1 (*continued*)

Citations/topics	ICL (*n* = 43)	ECL (*n* = 61)	GCL (*n* = 36)
Van Gog et al. (2009)	+	+	+
Formal simulation model of CLT			
Sawicka (2008)	+	+	+

Note. ICL, intrinsic cognitive load; ECL, extraneous cognitive load; GCL, germane cognitive load. + refers to an explicitly named load type, (+) refers to a load type being described without being explicitly named.

The 65 publications were inspected for the following aspects: (a) common topics covered by the publications, and (b) descriptions of the three types of cognitive load.

Table 1 shows a summary of the references, clustered according to similar topics. The largest group of publications (45 articles) referred to the design of educational environments. Several subgroups within this group could be identified: Seven publications dealt with dynamic representations, such as animations, video, or the combination of speech and pictures (Ayres, Marcus, Chan, & Qian, 2009; Guttormsen Schär & Kaiser, 2006; Homer, Plass, & Blake; 2008; Kalyuga, 2008; Korakakis, Pavlatou, Palyvos, & Spyrellis, 2009; Tudoreanu & Kraemer, 2008; Wong et al., 2009). A group of six publications looked at simulation environments (Holzinger, Kickmeier-Rust, Wassertheurer, & Hessinger, 2009; Horz, Winter, & Fries, 2009; Ik-Park, Lee, & Kim, 2009; Sawicka, Kopainsky, & Gonzalez, 2008; Sinclair, Renshaw, & Taylor, 2004; Wirth, Künsting, & Leutner, 2009). Learning with hypertexts was the scenario of another six publications (Amadieu, Tricot, & Marin, 2009; DeStefano & LeFevre, 2007; Madrid, Oostendorp, & Puerta Melguizo, 2009; Moos, 2009; Seufert, Jänen, & Brünken, 2007; Zumbach & Mohraz, 2008). Five papers focused on learning with worked examples (Caspersen & Bennedsen, 2007; Chang, Sung, & Lin, 2006; Gray, Clair, James, & Mead, 2007; Hilbert & Renkl, 2009; Schwonke et al., 2009). Three publications dealt with cooperative learning, (Kiili, 2006; Kirschner et al., 2009a, 2009b; Lyons, Lee, Quintana, & Soloway, 2006).

Further topics consisted of cognitive load measurement, the design of multimodal interfaces, cognitive load and decision making, the design of hypermedia and information search issues, game design, the modeling of distributed cognitive load in groups, analysis methods for cognitive processes, and a formal model of CLT. Forty-three publications explicitly named or circumscribed intrinsic cognitive load. With regard to extraneous cognitive load, this applied to 61 publications. Germane cognitive load was named or described by 36 publications. Thus, it can be stated that all three types of cognitive load have found their way into the HCI literature, with extraneous cognitive load being predominant. A closer look at the research questions of the 36 publications describing germane cognitive load revealed that only 17 of them dealt also with fostering germane cognitive load or balancing intrinsic and germane cognitive load (Amadieu et al., 2009; Ayres & Van Gog, 2009; Caspersen & Bennedsen, 2007; Cierniak, Scheiter, & Gerjets, 2009; Courtemanche, Najjar, & Mayers, 2008; Hilbert & Renkl, 2009; Holzinger et al., 2009; Horz et al., 2009; Kiili, 2006; Korakakis et al., 2009; Leutner, Leopold, & Sumfleth, 2009; Samaras, Bousiou, Giouvanakis, & Tarabanis, 2007; Sawicka, 2008; Sawicka et al., 2008; Seufert et al., 2007; Tuovinen, 2000; Van Gog, Kester, Nievelstein, Giesbers, & Paas, 2009). Within the publications dealing with multimodal user interfaces, the modality principle owned a prominent role. It was found that the use of multiple sensory channels at a time can increase total cognitive capacity.

5. Integration of HCI concepts and CLT concepts

To a certain extent, CLT concepts and HCI approaches and concepts have been explicitly integrated by researchers. For instance, Oviatt (2006) applied usability principles, such as making a system intuitive to use and easy to learn in order to decrease extraneous cognitive load. Sawicka et al. (2008) pointed out that designing usable learning environments reduces extraneous cognitive load and may contribute to improved learning. Similarly, Chalmers (2003) named CLT principles for decreasing extraneous cognitive load as a means of increasing the usability of educational computer systems. Clarke, Ayres, and Sweller (2005) showed that training learners to use a spreadsheet application prior to mathematics instruction reduces memory load compared to concurrently receiving instructions on spreadsheet usage and on mathematics. Also, with regard to learning to apply a software application, Van Nimwegen et al. (2006) referred to CLT and specifically the concept of germane cognitive load in order to explain why it may be sometimes disadvantageous to externalize information on the interface in order to reduce memory load. With the example of a conference booking system, it appeared that a system that externalized valid actions led to shallower thinking, less planning, and lower knowledge acquisition compared to a system without such a support.

To further integrate CLT and HCI approaches and concepts, we would like to propose two conceptual models and point out their implications for research related to educational software systems. The first model exemplifies what other researchers have already outlined: Cognitive load induced by using a software tool can be modeled as a specific component of extraneous cognitive load (cf. Clarke et al., 2005; Oviatt, 2006; Sawicka et al., 2008), with the other component being extraneous cognitive load due to instructional design (see Fig. 1). The amount of extraneous load due to software use is influenced by the complexity of the software, a suboptimal software design according to traditional usability goals, and the expertise of the learner with regard to the use of the software. Load can be lowered by designing highly usable software applications and by training learners to use the software (cf. Clarke et al., 2005; Oviatt, 2006; Salmon, 2000). If the software is very easy to use or if software usage can be automatized through training, the software component in extraneous cognitive load can be neglected. The model also clarifies the role of existing CLT principles and traditional HCI design principles related to a reduction of extraneous cognitive load due to ICT use. The latter relate to a reduction of extraneous cognitive load due to ICT use. CLT

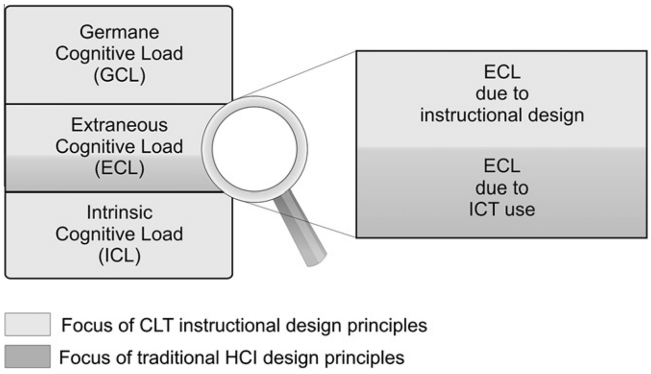

Fig. 1. Components of cognitive load in ICT- (information and communication technology) supported learning.

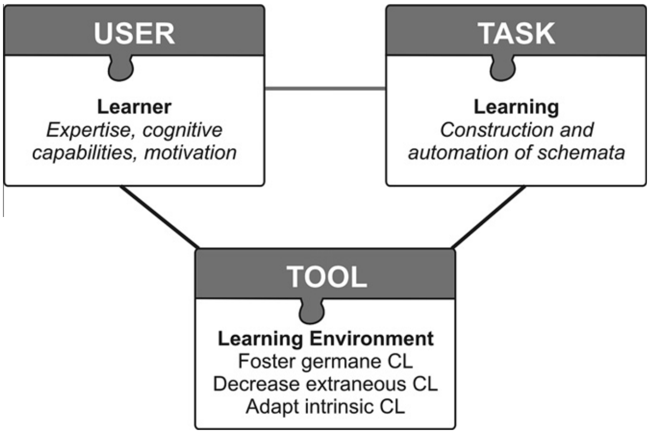

Fig. 2. User, task, and tool in an e-learning context, defined according to CLT. The goals of the tool are related to the three types of cognitive load (CL).

principles may also play a role in reducing this load component, namely when applied to design software training, a purpose CLT has already been successfully applied to (Chandler & Sweller, 1996). Furthermore, the model also explicitly points out an often pronounced request (Mayes & Fowler, 1999; Squires & Preece, 1999): Traditional usability principles are not sufficient for guaranteeing successful learning; further educational principles or expertise are required to foster germane learning processes.

As a second model, we propose the integration of CLT concepts into the usability concept (see Fig. 2). As described above, designing a usable application requires an understanding of its specific users and tasks (Mandel, 1997; Preece et al., 2002). In the case of educational software tools, CLT defines users as learners and the task as learning. Learners vary with regard to a range of relevant dimensions, such as level of prior knowledge with regard to the learning matter and to the software application, strategic memory skills, or motivation (Chalmers, 2003; Kalyuga et al., 2003; Schnotz et al., 2009; Seufert et al., 2009). At the highest level, the task of learning according to CLT would be the construction and automation of cognitive schemata. This construction process requires germane cognitive load. The three types of cognitive load occur during learning and can be influenced according to the instructional design principles developed in CLT (Sweller et al., 1998). As the first model described, existing usability principles can reduce the extraneous load induced by software usage. The goal of educational technology should be to adapt intrinsic load (for example, by assigning tasks with a suitable complexity to specific learners) to reduce extraneous cognitive load and to foster germane cognitive load, taking care that the overall amount of cognitive load remains within cognitive capacity. The model also helps to describe specific aspects of software design that are necessary for educational purposes. It sets the focus on cognitive processes rather than on fulfilling specific tasks. Germane load is a central concept in this model. It points out that, in contrast to the design of software in the work domain, in the learning context, an increase in cognitive load can be appreciable (cf. Tselios et al., 2008; Van Nimwegen et al., 2006).

6. Discussion and prospects

We have argued that by extending CLT research into scenarios that use complex software tools to support individual and group learning, as well as the creation of media by learners, CLT is faced with a set of issues that are related to HCI research. We therefore investigated whether CLT and HCI concepts are compatible and to what extent CLT concepts have been adopted in the HCI literature. It appears that both fields share basic assumptions about the human cognitive system, and that both fields have focused on a reduction of irrelevant load in a first phase. More recently, both fields have adopted the notion that it can be beneficial to design applications that increase cognitive load. The literature search within the HCI related database "Guide to Computing Literature" showed that CLT and specifically the three types of cognitive load have found their way into the HCI literature, germane cognitive load, however, to a smaller extent. A reason for this might be that the use of germane cognitive load to try to raise cognitive load contradicts the still predominant general goal in HCI to reduce cognitive load (cf. Sharp et al., 2007).

Two models were proposed to integrate CLT concepts and basic HCI concepts further. The models are intended as high-level conceptual aids that offer implications for research and the design of complex educational software. The first model describes cognitive load due to software as a specific component of extraneous load, according to the approaches of Clarke et al. (2005), Oviatt (2006), and Sawicka et al. (2008). This model points out the importance of designing easy-to-use and easy-to-learn software and of providing software training as early as possible within the learning process.

The second model integrated CLT concepts into the basic components of user-centered design: User, task, and tool. The concept of germane cognitive load is crucial in this model, as it exemplifies the particularities of designing software tools to support learning: The highest-level goal of using such a tool is to construct mental schemata. Hence, educational software needs to enable germane cognitive load to take place, and increasing germane load can be appreciable.

Several areas can be identified for future research: For instance, CLT research involving complex educational software may profit from taking existing usability guidelines and principles into account in order to reduce extraneous cognitive load. Furthermore, the applicability of existing CLT educational design principles for educational software design should be evaluated empirically. It should not be assumed that CLT and its instructional design principles offer off-the-shelf solutions for educational technology. According to user-centered software development methods, such guidelines should always be applied based on an in-depth understanding of the users and their specific tasks or goals (Preece et al., 2002).

This leads to another area of potential future research, namely, methods for the design and evaluation of educational software systems that take CLT concepts into account. For example, in order to gain an in-depth understanding of cognitive processes during the use of complex educational software, it could be interesting to apply think-aloud methods (Sharp et al., 2007; Van Gog et al., 2009) and to relate the users' comments to germane and extraneous cognitive load concerning the learning matter, as well as the software usage.

Moreover, the impact of learner characteristics in relation to cognitive load and CLT principles should be investigated further. Whereas prior knowledge with regard to the learning matter has already been investigated to some extent, CLT research concerning complex software systems would benefit from also taking into account prior knowledge with regard to software usage. An educational software system may lead to different learning outcomes depending on the level of software expertise (Clarke et al., 2005). Further learner characteristics, such as the motivation or interest of learners, have only begun to play a role in CLT and HCI research (Schnotz et al., 2009; Sharp et al., 2007).

Furthermore, it would be interesting to investigate how the more recent research on user experience (cf. Preece et al., 2002) relates to cognitive load: For example, how do user experience factors, such as the visual aesthetics of educational software, influence cognitive load, learning outcomes, or mediating components such as motivation (cf. Holzinger et al., 2009)?

Finally, HCI research has dealt with new methods to measure cognitive load unobtrusively, for example, by analyzing input features (Ruiz, Taib, Shi, Choi, & Chen, 2007). CLT may profit from making use of these new methods in empirical research involving complex educational software.

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