The conceptualisation of cognitive tools in learning and technology: A review

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The term *cognitive tool* has been used in many areas of academic specialisation, where it has taken on multiple connotations. In this historical and systematic review, we investigate the conceptualisation of cognitive tools in the learning sciences and educational technology. First, the theory of cognitive tools vis-à-vis learning and development is traced from Vygotsky and Soviet psychology through to its use in current educational technology and learning design. Second, we present a systematic review of cognitive tools in peer-reviewed research literature. We found the term cognitive tool was often used vaguely or with extreme generality. When used more specifically, it referred to communication methods such as visualisations, metaphors, symbols, and hypermedia; or interactive interfaces and environments such as templates, databases, simulations, games, and collaborative media. We offer a definition of software-based cognitive tools founded on the attributes of *representation*, *interactivity*, and *distributed cognition*, which commonly feature in the work of influential theorists; and we explain implications of the definition for designing, evaluating, and researching learning technologies.

The term *cognitive tool* has seen extensive usage in a range of education-related academic disciplines. Theorists or researchers taking up the term often gave it a sense that differed, sometimes radically, from the way it was used by prior writers. Throughout its history as an intellectual port of call, the notion of cognitive tool has been linked with cognitive development (Vygotsky, 1930/1999), computer technologies (Pea, 1985), distributed cognition (Salomon, 1993), constructivism (Jonassen, 1995), scaffolded cognitive processing, knowledge visualisation, metaphor, and a host of other ideas detailed in this article. The various interpretations seem so diverse, and are sometimes presented with such little reference to prior work, we believe there is a need for an inquiry into the origins of the concept, how it has evolved to inhabit specialised intellectual niches, and whether its divergent meanings retain a common or core sense that offers value in the field of educational technology and learning design.

In this review, we examine the theory of cognitive tools and its implications for designing learning technologies. First, we historically trace the main themes of the concept from its roots in the Soviet psychology of Vygotsky and his associates through to its widespread use in the learning sciences and the study of educational technology. Second, we report a systematic review of peer-reviewed journal articles that recorded and categorised uses of the term cognitive tool. Finally, we consider what ideas lie at the core of the various conceptualisations of cognitive tools, judge which of these ideas have a continuing role to play in the learning sciences, and describe their implications for designing learning technologies.

Cognitive tools in the history of psychology and learning design origins in Soviet psychology

Vygotsky's approach to human psychology, developed in the context of an early twentieth century science he found to be in crisis, introduced many new and important concepts. A central idea of his new psychological theory was a focus on the existence of internal and external tools that transform the structure of mental functioning (Cole & Gajdamaschko, 2007; Gajdamaschko, 2015). Without these tools, Vygotsky insisted, we can't bridge the gap between genetically inherited, mainly reactive functions and complex, cultural functions. Cultural functions, or as Vygotsky called them, higher psychological functions, are mediated by tools, and the inclusion of tools into their structure allows us to explain the crucial role of culture and history in psychological development (Gajdamaschko, 2015).

Vygotsky's focus on mediation, the central notion of his views of learning and development, represents a departure from other psychological and educational theories. He argued that the inclusion of cultural tools in the process of psychological growth can alter the trajectory or pattern of development, enabling a learner to solve much more sophisticated problems and empowering her with the wisdom of previous generations via the meaning of the tool (Vygotsky, 1930/1997). External and internal tools are instruments that learners use to modify and regulate their behaviour, and the analysis of these tools is an essential element of Vygotsky's approach to understanding human development. In the developmental process, Vygotsky explains, pre-existing mental processes are joined and transformed by culturally designed tools that are internalised through social interaction. The resulting higher psychological functions are viewed by Vygotsky as self-regulated processes that are cultural, historical, and social in their origin. Just as the introduction of a new type of machine into a workplace can lead to a radical reorganisation of work and division of labour, internalisation of psychological tools into mental functioning can radically reshape learners' thinking.

Vygotsky's (1978) claim contrasts sharply with psychological theories, especially Piagetian theory, which focuses on the developing child as an individual agent. For Vygotsky, culture, via the mediation of tools, is fundamentally integrated within a person's mental function and does not merely facilitate or overlie their natural development. As Wertsch (1998) put it, to understand the role of culture and society in human development we must study "the irreducible tension between agent and mediational means" (p. 25), where the tools empower but simultaneously impose their own constraints on the mental functioning of the learner.

Current conceptualisations of cognitive tools in the field of learning technologies are rooted in, but different from, the Vygotskian theory of cognitive tools. For Vygotsky, cognitive tools are omnipresent and inevitable means by which thinking is shaped by culture, and the question is not whether the use of cognitive tools is desirable but rather whether the cognitive tools being internalised by learners are the most suitable for promoting their cognitive development. For several decades, Vygotskian educational researchers have evaluated and redesigned the cognitive tools used in Russian schools and in so doing have significantly shaped the Russian curricula. For example, Davydov and Tsvetkovich (1991) noted the problem inherent in having children develop the concept of number as a by-product of counting operations, as is usually the case in traditional mathematics classrooms. In Vygotskian terms, counting is a cognitive tool (Schmittau, 2003). When children identify numbers by counting, they interpret them only as positive integers, and this persistent misconception hinders their later understanding of fractions and irrational numbers. In Davydov and Tsvetkovich's curriculum, which has been established in Russia for many years, the concept of number is grounded in the operation of measurement rather than the operation of counting. Furthermore, in their curriculum, children progress from comparing the length (or other dimension) of nearby objects to comparing things that can't be physically aligned next to each other using a portable, intermediate object (e.g., an eraser), and finally to measuring objects using any smaller object as the unit of measurement. A measurement is expressed as the ratio of the length of an object to the length of measurement unit. Grounding the concept of number in the cognitive tool of measurement allows for the possibility, in later grades, of a fraction instead of a whole number emerging as the measured quantity. Crucially, this means the later introduction of multiplication, fractions and irrational numbers does not require learners to reconceptualise the meaning of number. This example shows how having learners internalise a different or redesigned cognitive tool can alter how easily they, years later, acquire more advanced concepts.

Technologies and designs for learning

Before 1985, American theorists described the use of software tools as amplifying learners' abilities in terms that showed no influence from Vygotskian theory. Taylor (1980) saw the educational value of software tools (e.g., calculators) lying only in their capacity to aid completion of requisite but secondary tasks. They might "teach the user something during use, but any such teaching is most likely accidental and not the result of any design to teach" (p. 8). Pea (1985), however, advocated shifting the conceptualisation of learning technologies from the metaphor of cognitive amplification to one of cognitive reorganisation. He argued the metaphor of amplification describes gains in the efficiency of existing cognitive processes, but that cognitive tools have the potential to change how cognition is organised. Citing Vygotsky (1962) and his colleague Luria (1976), Pea connected the tool-like function of symbols in Vygotsky's understanding of cognitive activity and the role of the computer as a symbol manipulator. Unlike amplification, reorganisation implies qualitative changes in how learners perceive and operate on their world. The technologies that Pea saw as capable of promoting cognitive reorganisation included programmable tools such as electronic spreadsheets and interactive programming environments, and also software that for the purposes of this article we call *digital learning environments*. Digital learning environments simulate learnable features of the world or dynamically represent abstract ideas and relationships. Digital learning environments include microworlds for engaging with Newtonian mechanics (DiSessa, 1983), geometry (Scher, 2000), and medical diagnostics (Lajoie, Lavigne, Guerrera, & Munsie, 2001); and intelligent tutoring systems (ITSs) that offer an interface in which students can choose which operations to apply in performing each step of solving a problem (Anderson, Corbett, Koedinger, & Pelletier, 1995). Kozma (1987) described how cognitive tools present models that can be internalised, as when a student develops the ability to think structurally about an essay through working with the outline function in a word processor.

Building on Pea's (1985) ideas, Salomon, Perkins, and Globerson (1991) distinguished between "tools that work for us" and "tools with which we work" (p. 3). Whereas the former are devices that afford little direct interaction (e.g., a communications satellite), the latter are cognitive tools we partner with to accomplish tasks (e.g., an electronic spreadsheet). Examining how students work with cognitive tools or "technologies of the mind" (p. 4), Salomon et al. echoed Pea's contrast between the metaphors of amplification and reorganisation – they differentiated the "effects with" the tools, which are varieties of enhanced performance, and the potential "effects of" the tools, which are transferable, long term changes in students' abilities. They argued that desired educative effects of cognitive tools cannot be expected automatically but must be designed into the tools and the contexts in which they are used. Salomon (1993) observed that computer-based tools can take on much of the cognitive effort required by a task and thereby offer their users an intellectual partnership. He noted the Vygotskian character of this exchange and how, when used for pedagogical purposes, the operations shared by distributed cognition often become internalised by the learner.

Drawing on Piagetian learning theory, Duchastel (1990) distinguished two kinds of cognitive tools for learning. "Power tools" (p. 4) are environments in which learners might solve problems, create art, or write computer programs, perhaps with guidance from the system. He saw power tools as provoking Piagetian accommodation via schema restructuring and resolution of fundamental misconceptions. "Assimilatory tools" (p. 4) augment learners' ability to adapt new information to fit into existing schemas. Duchastel regarded encyclopedias, textbooks, and hypermedia as examples of assimilatory tools.

Tools for constructivist learning

The essence of constructivism is the belief, advocated by Piaget and now widely accepted by many psychologists and educational theorists, that humans actively build much or all of what they know and act as decision-making agents in doing so (Moshman, 1982; Von Glaserfeld, 1989). During the 1990s, as the constructivist principle gained currency in the field of learning technologies, computer-based cognitive tools were often portrayed as key components of learning environments in which learners could operate as they engaged with a subject as autonomous agents (Dalgarno, 2001).

Jonassen and his colleagues wrote extensively about computer-based cognitive tools, sometimes calling them "mindtools", and argued for their significance in constructivist learning (Jonassen, 1995, 1996, 2000; Jonassen & Carr, 2000; Jonassen, Carr, & Yueh, 1998; Jonassen & Reeves, 1996). Cognitive tools are defined as knowledge representation tools that can "enhance the power of human beings during thinking, problem solving, and learning" (Jonassen & Reeves, 1996, p. 693), "activate cognitive and metacognitive learning strategies" (Jonassen, 1992, p. 2), and "function as intellectual partners with the learner in order to engage and facilitate critical thinking and higher-order learning'' (Jonassen, 1996, p. 9). While Salomon (1993) saw computer-based cognitive tools as scaffolds whose benefits lay in the cognitive effects remaining after the tools have been removed, Jonassen and Reeves argued that performance with a tool can be a goal in itself because technologies are an inevitable and ongoing component of contemporary contexts. They believed cognitive tools had the potential to open a path to constructivist learning and transferable knowledge in educational systems dominated by routinised practice and reproduction of given information. Jonassen (2000) described how students' intentional engagement with cognitive tools promotes meaningful learning and reflective thinking.

Noting that each type of computer-based cognitive tool uses a particular formalism to organise information, Jonassen and his colleagues argued that the availability of many types of these tools, from spreadsheets to hypermedia, affords opportunities for multiple representation of knowledge (Jonassen & Carr, 2000; Jonassen et al., 1998). They claimed students would reap far greater benefit from designing and building new artefacts with the tools rather than interacting with them as users or consumers. Students who work with and internalise multiple representations were theorised to have a deeper and more flexible understanding of a topic that would transfer more naturally to real-life situations. Jonassen and his colleagues categorised databases and concept mapping software as *semantic organisation* tools because both implement formalisms for explicitly representing relationships between objects or concepts. Spreadsheets, system modelling software, expert systems, and programmable environments were grouped together as *dynamic modelling* tools because they allow students to build models so they can ask “what if” questions whose answers depend on hypothetical or variable conditions. Software that can generate images of abstract or normally invisible phenomena, like molecular structures, were counted as *visualisation* tools. Hypermedia publishing tools, perhaps best exemplified today by Wikipedia, were categorised as *knowledge construction* tools. Finally, online conferencing software, computer-supported collaborative argumentation systems, and the like were categorised as *socially shared* cognitive tools. Jonassen (2011) emphasised that tools supplied in a learning environment should be selected according the types of thinking that require scaffolding. He observed, for example, that solving design problems requires construction of mental models, a process that can be scaffolded by the use of modelling software. Much of the research over the last decade reporting on diverse cognitive tools continued to cite the taxonomy developed by Jonassen and Carr (2000) and Jonassen et al. (1998). Among these, Collins and Knoetze (2014) described how undergraduates can develop procedural and conceptual knowledge by working with an expert system shell on discovery learning tasks, and Herrington and Parker (2013) studied the use of web-based tools for authentic learning in first-year teacher education.

Whereas Vygotsky (1978) emphasised the interaction between the learner and teacher (or more knowledgeable other) and saw the cognitive tool as mediating this key interaction, Pea (1985), Salomon (1993), and Jonassen (1992) foregrounded interactions between the learner and the cognitive tool. Jonassen and Reeves (1996) claimed that cognitive tools should be “learner-controlled not teacher-controlled” because they fail when used for “traditional academic tasks set by teachers” (p. 697). They admitted that teachers have a guiding role as long as the problems to which cognitive tools are applied originate with learners. This is a far cry from the Vygotskian understanding that cognitive tools constrain as well as empower the endogenous predispositions of learners (Wertsch, 1998).

Jonassen and Reeves (1996) argued against the use of computer-based ITSs because they saw such systems as only mimicking the traditional controlling role of teachers. In the introductory chapter to their book *Computers as Cognitive Tools*, Derry and Lajoie (1993) outlined a fundamental division then existing in the field of learning technology between the *model builders* designing ITSs that incorporate student models (Koedinger & Anderson, 1993) and *non-modelers* like Salomon (1993) and Jonassen (1992).

B. Kim and Reeves (2007) noted this same lack of consensus in the conceptualisation of cognitive tools and observed that as the term became widely used in the field of learning technologies it lost its original grounding in psychological theory. As justification of the earlier categorisation by Jonassen and Carr (2000) and Jonassen et al. (1998), they proposed only software programs that contribute a middle level of executive control qualify as cognitive tools. Programming languages were excluded because they are too passive, and ITSs because they take on too much control. Kim and Reeves considered databases, concept mapping tools, simulation tools, and microworlds to be cognitive tools because they contribute expertise that shapes the nature of the activity and at the same time leave much of the higher-order decision-making to the learner.

Student-centred learning theorists Iiyoshi, Hannafin, and Wang (2005) conceptualised cognitive tools as instrumental in reducing the cognitive load associated with open learning environments and as essential catalysts for learning in complex environments. M. C. Kim (2012) reviewed the theoretical foundations of software-based cognitive tools and presented a conceptualisation emphasising social construction of scientific knowledge in collaborative learning environments. More than earlier constructivist theorists, Kim’s social-constructivist conceptualisation recognised the importance of instructors’ roles in selecting problems and projects, focusing students’ attention, diagnosing student difficulties, providing just-in-time assistance, mediating student collaborations, and providing formative feedback.

Metacognition and self-regulated learning

Computer-based cognitive tools can be used to scaffold learners' monitoring and control of their cognitive processes as they solve problems and work towards learning goals. Metacognition is the awareness of one's own thinking and capacity for strategic action, and self-regulated learning is the use of that understanding to self-direct knowledge construction (Dinsmore, Alexander, & Loughlin, 2008). Cognitive tools can be designed to make metacognition more explicit, and thereby expand learners' capacity for agentic control. Lajoie (1993) described metacognitive support functions that cognitive tools can offer students engaged in problem-solving. Learning to solve ill-structured problems such as diagnosing diseases in BioWorld (a hospital simulation that provides a realistic environment for students to learn about diseases through solving specific patient cases, Lajoie et al., 2001) can involve extended explorations of a large and complex problem space. An essential function of cognitive tools in such problem-solving environments is supporting the evaluation of competing hypotheses. To that end, BioWorld provided an *argumentation palette* that allowed students to manage their hypotheses and a *belief meter* that they could use to record their level of confidence in each hypothesis. Re-presenting past actions and judgements to the learner via cognitive tools in problem-solving environments such as BioWorld was hypothesised to model and promote internalisation of expert metacognitive processes (Lajoie, 1993).

A survey of cognitive tools in peer-reviewed research

We conducted a systematic survey of references to cognitive tools in articles published in peer-reviewed journals up to and including 2018. The purpose of the survey was to examine quantitatively how the concept of cognitive tools has been used in research and theory relating to learning and instruction. This review addressed the following questions:

- How have references to cognitive tools changed over time?
- What types of cognitive tools are being described and empirically investigated?
- Which areas of scholarship in the learning sciences are making frequent references to cognitive tools?
- In empirical research relating to cognitive tools, which levels of schooling and subjects have been studied?

Method

A multiphase procedure, shown in Figure 1, was used for searching and coding published articles. The phases of the procedure were (a) systematic searching of electronic databases, (b) screening to exclude documents that did not meet eligibility criteria, and (c) structured coding of eligible articles.

To identify potentially relevant studies, a systematic electronic search was performed on three electronic databases (ERIC, PsycINFO, and Web of Science) selected for their coverage of research in education, psychology and the social sciences respectively. These were searched using the keyword "cognitive tool*" with search parameters set to capture peer-reviewed publications. The search was conducted in two stages. The first stage was conducted in March and April of 2016 and returned 1044 records. The second stage, covering 2016 to 2018, was conducted in 31 December 2018 and returned 101 records. A total of 1145 records were identified in these searches (ERIC, 235; PsycINFO, 396; Web of Science, 514).

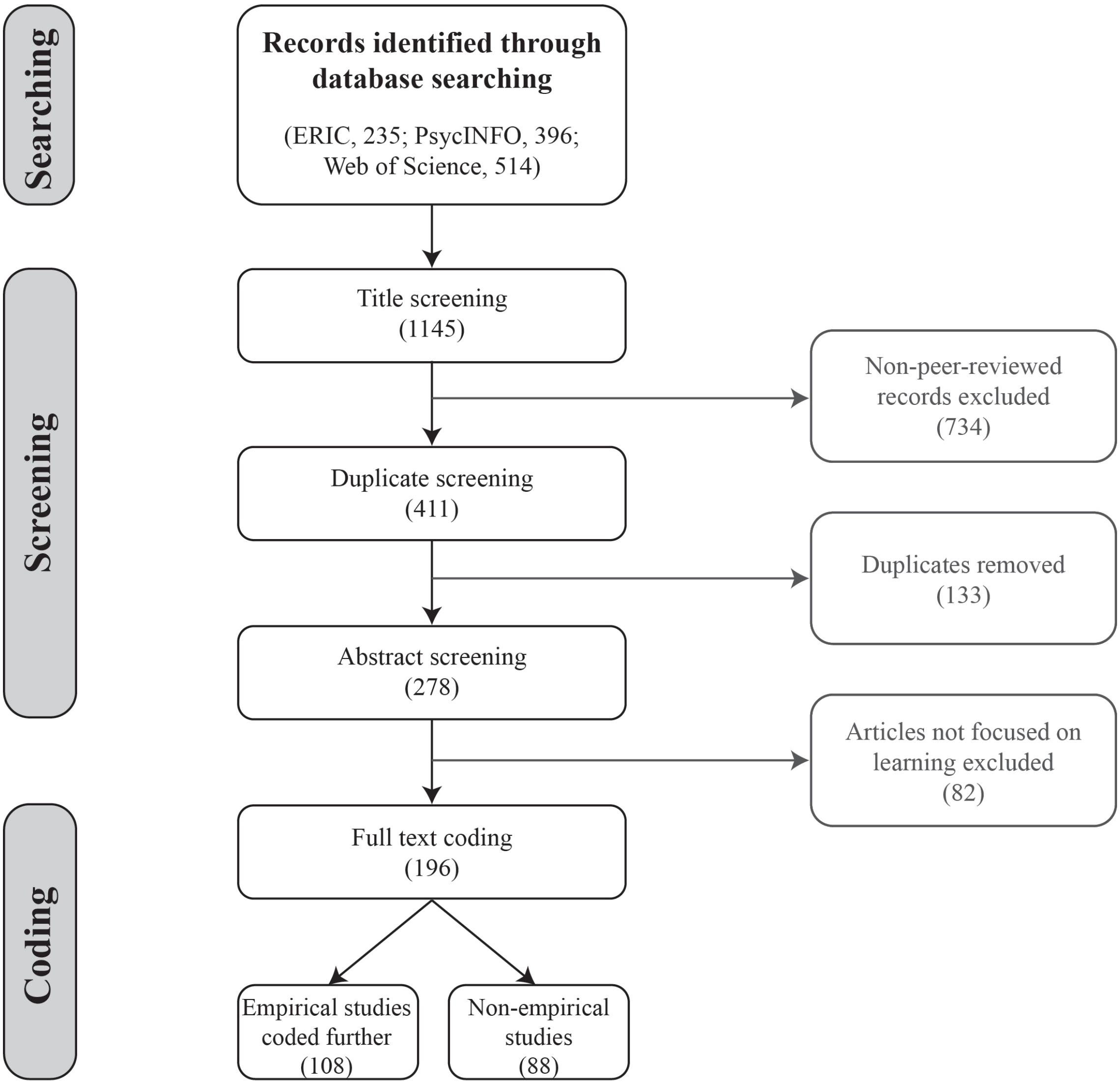

Figure 1. Multiphase procedure for searching, screening and coding articles

Screening

Titles and metadata were examined to exclude all but peer-reviewed journal articles. We also excluded articles not written in English and articles unrelated to learning in which the term cognitive tool referred to a cognitive assessment instrument. A total of 734 records were excluded and 411 peer-reviewed articles were imported to the Mendeley reference management software. Using Mendeley, 133 duplicates were removed, and the remaining 278 peer-reviewed articles were retained. In the abstract screening step, 82 articles were excluded because the cognitive tools they identified were not intended to promote learning of identified concepts, skills, interests, or motivations, and 196 peer-reviewed articles were eligible for further analysis.

Coding

Articles were coded for 7 variables: year of publication, number of references to the term cognitive tool, academic specialisation, type of cognitive tool, type of study (empirical vs. non-empirical), and for empirical studies, level of schooling and subject area. Some variables could be objectively coded by one of the researchers and required no reliability checking. For more subjective variables with predetermined codes, two researchers coded 20 randomly selected articles and obtained an average inter-rater agreement (Kappa) of $\kappa = .82$. After discrepancies in coding were discussed and resolved, one researcher coded the remaining articles. For variables which required the iterative development of codes, two researchers reviewed and discussed each article to obtain full agreement. The articles were coded as empirical if they reported gathering qualitative or quantitative data regarding a cognitive tool.

Results

We found 196 peer-reviewed journal articles that referred to learning with cognitive tools (see Appendix for references). Figure 2 shows the frequency of these in the 37 years from 1982 to 2018. Very few articles (5%) referred to cognitive tools before 1998, and 75% appeared after 2004. A total of 116 (59.2%) referred to cognitive tools as technologies such as specific software applications or information and communications technology (ICT) in general, while the remaining 80 (40.8%) used the term to refer to non-technological tools, such as language, symbols, schemas, or metaphors. In the years 2005 to 2009, however, there was a marked increase (to 74%) in the proportion of articles referring to technological cognitive tools. The figure indicates usage of the term declined somewhat in recent years yet retains considerable currency.

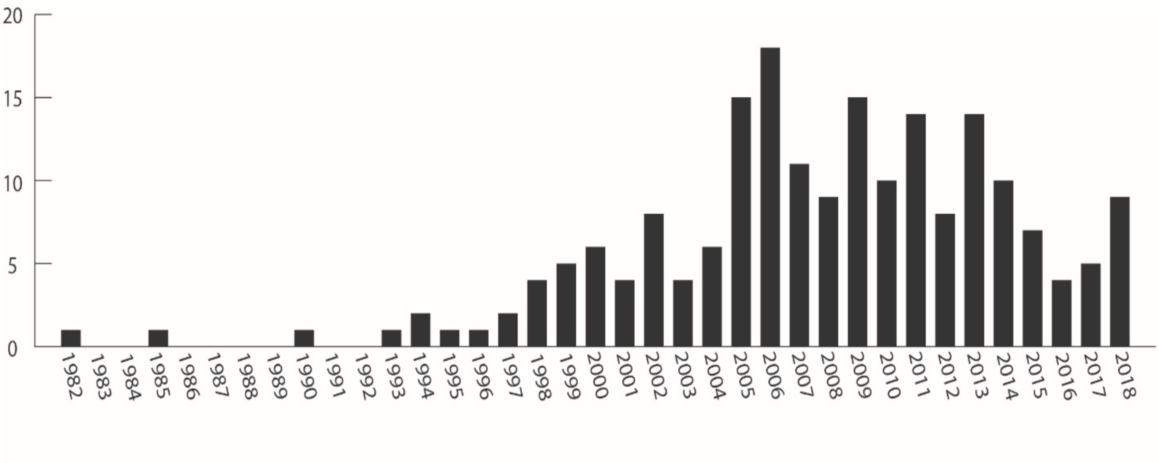

Figure 2. Distribution over time of articles referring to the use of cognitive tools for learning

Table 1 shows the distribution of frequencies with which the articles referred to cognitive tools. Notably, out of 196 articles, 29 referred to cognitive tools only once, and 29 only twice. We found most of the articles provided no definition of the term and no explanation for why it was used. For instance, in an article titled "Strategy Instruction from a Sociocognitive Perspective", Lenski and Nierstheimer (2002) used the term only once, in the abstract, to refer to reading and writing strategies. They gave no justification for identifying the strategies as cognitive tools and gave no indication as to which conceptualisation of cognitive tools they were referring to. Articles that made more references to the term were more likely to provide definitions and explanations for using it.

Table 1
Distribution of the frequency with which articles referred to cognitive tools

Frequency of references to cognitive tools	Articles	Cumulative percentage
1 time	29	14.8
2 times	29	29.6
3 to 10 times	79	69.9
More than 10 times	59	100

Table 2 shows the term cognitive tool was used mostly in areas of academic specialisation relating to education. In the table, "education" refers to educational specializations other than educational technology and educational psychology; and "other" refers to miscellaneous specialisations such as computer science, philosophy, and medicine. We observed that across the areas of academic specialisation, the concept of cognitive tool was used for widely varying purposes. For example, in sports psychology, it was used by Schack (2004), citing Vygotsky (1978), to emphasise the symbolic character of "basic action concepts" that constitute complex movements. Working in linguistics, Chen, Li, Li, Wang, and Wu (2013) referred to bilingualism as a cognitive tool that affects the phonological awareness of children; while Bender and Beller (2012) developed a psychological hypothesis that finger counting is a culturally encoded and embodied cognitive tool.

Table 2
Academic specialisation of 181 articles referring to cognitive tools

Academic specialisation	Articles	Percentage
Education	71	36.2
Educational technology	57	29.1
Educational psychology	30	15.3
Psychology	20	10.2
Linguistics	6	3.1
Other	11	6.1

We have already noted how theorists have used the term cognitive tools to refer to a wide variety of concepts and software, and our systematic review found evidence for this variety across the research literature. Figure 3 shows the frequency distribution for the types we coded. Our categorisation scheme was adapted from the five categories identified by Jonassen et al. (1998) which we added to, modified, and renamed to accommodate the references to cognitive tools we encountered.

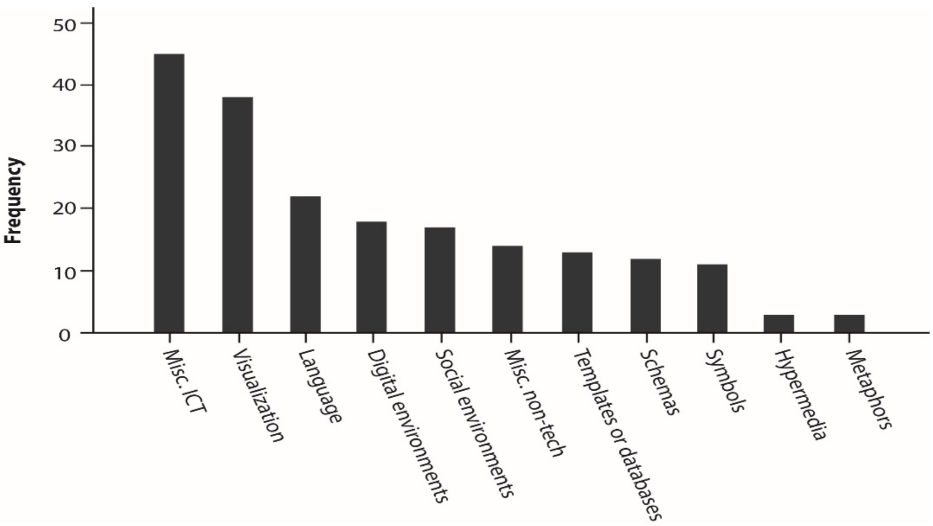

Figure 3. Articles categorised by the type of cognitive tool on which they focused

The template or database category included tools that enabled learners to organise information and identify the relationship between items (Li & Liu, 2007). The visualisation category included concept maps and Vee diagrams (Afamasaga-fuata'i, 2008), Geometer's Sketchpad (Contreras, 2011), computer-based animations to facilitate learning geography (Edsall & Wentz, 2007), and other types of visualisations. The digital environments category included references to specific simulations (e.g., Hung, 2008); microworlds (e.g., Poitras, Lajoie, & Hong, 2012) and computer games (e.g., Martinovic, Burgess, Pomerleau, & Marin, 2015). The social environments category included specific references to educational media that facilitated communication among learners, such as online discussion forums (Stahl, 2006) and argument-sharing tools (e.g., Tambouris, Zotou, & Tarabanis, 2014).The language category covered references to non-technological tools denoting word knowledge (Mirolli, & Parisi, 2009); language acquisition (De la Colina & Mayo, 2009), and so on. The schema category covered articles referring to either the general concept of schema (e.g., Arievitch, & Stetsenko, 2000) or instances of schemas such as mental models of acids for chemistry students (e.g., McClary & Talanquer, 2011). As shown in Figure 3, categories appearing less frequently were symbols (e.g., Miller, 2000), hypermedia (Yildirim, 2005), and metaphors (Zheng, 2015).

Two miscellaneous categories were created to account for references to tools that could not be readily classified or were extremely general. The miscellaneous ICT category was used for all general references to ICT. The miscellaneous non-technology category covered a wide variety of concepts or operations that authors claimed to be cognitive tools, such as inductive generalisation when used by children to make sense of their environment (Puche-Navarro & Rodriguez-Burgos, 2015) and pedagogical literacy when used by teachers to develop how they reason about their professional practice (Maclellan, 2008).

There were 108 empirical studies, and the other 88 articles were non-empirical reviews or theoretical analyses. The empirical studies investigated the use of cognitive tools on participants at different levels of schooling consisting of preschool (6), elementary (22), secondary (18), undergraduate (39), graduate (2), in-service teachers or instructors (10), adult language learners (5), and others (6). These studies most often used academic content from science, mathematics, and language learning. Many of them, however, were laboratory studies of motivation, problem-solving, and learning strategies that used content not necessarily drawn from academic programs. Most of the studies investigating the use of cognitive tools by university students gathered data from courses in which they enrolled. In the 61 empirical studies examining the effectiveness of using cognitive tools to enhance learning or motivation, 42 (68.9%) claimed the tools were effective, 12 (19.7%) found no significant effect, and 7 (11.5%) observed that other factors such as individual difference could moderate the effects of using the tools.

Knowledge representation, interactivity, and distributed cognition

Over time, the conceptualisation of cognitive tools has taken on multiple new meanings and shifted markedly from its roots in Soviet psychology. Vygotsky (1978) conceived of cognitive tools as constituents of culture that mediate instructional interactions and are internalised to become integral to learners' psychology and behaviour. Later, educational technology theorists such as Jonassen invoked different and sometimes conflicting conceptualisations to identify several types of software programs as cognitive tools and described how using them reorganises the cognitive structures of learners. Our systematic review showed how the term has gained significant currency in peer-reviewed research – most prominently in the field of educational technology but also educational psychology and other areas of educational research.

We found authors often claimed that the learning technologies they wrote about were cognitive tools without defining the term and without describing which features qualify the technology as a cognitive tool. Given the varying meanings and interpretations encountered in this review, we recommend that authors explain how they interpret the term cognitive tool, and – if they are referring to a particular diagram, idea, interface, or software application – explain why their purported instance should be considered a cognitive tool. The lack of definitional consensus also implies that, rather than review research on the broad concept of cognitive tools, meta-analyses should focus on specific features or categories of cognitive tools such as learner control in hypermedia environments (Scheiter & Gerjets, 2007) or the instructional effectiveness of visualisation tools (McElhaney, Chang, Chiu, & Linn, 2015).

Although we found disagreement about the definition of cognitive tools, we believe a core conceptualisation consisting of three attributes has emerged from Vygotsky (1978), Pea (1985), Salomon (1993), Jonassen (1992), Lajoie (1992), and several other theorists reviewed in the initial section of this article. Two of the attributes are alluded to by Preiss and Sternberg (2006, p. 15) when they explain that technologies designed as cognitive tools:

> predominantly afford transformations on the symbolic aspects of cultural life and, eventually, transformations of the users of those technologies. In so doing, cognitive tools, as systems of representation, play a central role in both cultural evolution and cognitive development.

First, a cognitive tool is a system of concepts, and sometimes operations, represented to a learner in a form or technology that supports goal-oriented cognitive processing. The idea of a cognitive tool as knowledge *representation* runs through the work of almost all the theorists we have discussed. As a current example, the Dialectical Map (DM) is a type of interactive visualisation software that individual undergraduate students at Simon Fraser University use to construct arguments (Nesbit, Niu, & Liu, 2019; Niu, 2016). Featuring a structure similar to an argumentation Vee diagram (Nussbaum, 2008), it provides text boxes for claims, reasons, warrants, and evidence that learners fill in and manipulate to show the pro and con sides of an argument. As a cognitive tool, it represents the culturally evolved constituents of argumentation and the relationships among them.

Second, as a result of extended interactivity with a cognitive tool, students internalise its related concepts and operations and may eventually be able to perform tasks that require those components without an external representation or device. As students use the DM to construct arguments over multiple occasions, they gradually reorganise their argumentation schema and eventually no longer need the software to construct arguments with warrants, rebuttals, and other advanced features. The idea that using knowledge representation tools reorganises or shapes learners' cognition was discussed by Pea (1985) and later others (Jonassen, 2000; Salomon et al., 1991).

The third attribute of a cognitive tool lies in its capacity for sustaining *distributed cognition* (Dror & Harnad, 2008). While they are searching for and generating ideas to enter into the DM, students refer to it to keep track of which parts of a good argument have been assembled and which remain to be done. Their memory for key aspects of the task is partially outsourced to the tool. Many software tools perform computational operations more efficiently than is possible by a human, thereby enabling distributed cognitive *processing* (Jonassen et al., 1998). There is often no intention to internalise the operations performed by this type of tool, but instead to continue relying on the device indefinitely. We can identify such devices as cognitive tools and *tools with which we work* (Salomon et al., 1991) if in using them students learn how to invoke specific outsourced operations and the conditions under which to do so. University students who learn applied statistics by working with specialised statistical packages (e.g., SPSS) or languages such as or R usually continue to rely on the tools in more advanced courses or in any subsequent work as researchers. Nevertheless, working with such tools teaches them a great deal about the situations in which each statistical function should be used and the inputs and output for each function.

What implications does our definition have within the field of educational technology and learning design? Theorists have debated whether ITSs can be regarded as cognitive tools, with some arguing for (Koedinger & Anderson, 1993; Pea, 1985) and others against (Jonassen, 1995; B. Kim & Reeves, 2007). The interface for one version of the Algebra Cognitive Tutor ITS (Brunstein, Betts, & Anderson, 2009, p. 792) provides a "transformation" menu from which students can choose one of four algebraic operations (e.g., "add to both sides"). At first, the ITS performs the selected operation, and at a later stage the student is expected to perform the operation. The list of available algebraic transformation operations provided by the menu qualifies as a simple cognitive tool because it represents task-relevant knowledge that can be internalised through repeated use of the tool. Also, the operations performed by the transformation menu afford distribution of cognitive operations to an external tool. The interface of the Algebra Cognitive Tutor has other features (e.g., the simplification menu) that can be regarded as cognitive tools for similar reasons. From our definition, then, the student interface of an ITS, or a component of the interface, can potentially be a cognitive tool.

What about more open learning environments like those discussed by Jonassen (1995) within which learners are able to imagine and then construct objects? Scratch is a programming environment designed to foster computational thinking (Resnick et al., 2009). Instead of keying in syntax-conforming code, students snap together virtual blocks shaped in ways that reflect their functionality. For example, the Repeat operation is represented by a C-shaped block into which the learner can snap the blocks to be iterated. Scratch has several key characteristics that qualify it as a cognitive tool. It represents key concepts and relationships of computational thinking, allows for cognitive processes to be distributed externally, and demands repeated meaningful interaction. Like the Algebra Cognitive Tutor that makes visible all available algebraic operations, the Scratch interface lowers the barrier to computational expression by displaying all the pluggable blocks from which programs can be constructed.

Implications for design and research

A complete account of principles for designing cognitive tools is outside the scope of this article, and here we merely demonstrate by example how three design principles flow, in part, from the conceptualisation of cognitive tools presented in the previous section. First, tools should be designed to represent knowledge in a way that is incompatible with common misconceptions and shows with special clarity concepts that students commonly find challenging or confusing. Second, the tool should be designed in such a way that novices can frequently interact with or refer to it as they complete tasks. Third, the tool should support students completing a challenging task by enabling them to offload or distribute to the tool memory or operations required by the task. These three principles – designing for representation, interactivity, and distributed cognition – imply that designers must develop clear learning goals and identify the barriers students encounter in attaining them.

Conclusion

In this concluding section, we illustrate how the three principles are evident in the design of the DM (Nesbit et al., 2019; Niu, 2016) and nStudy (Winne, Nesbit, & Popowich, 2017), another learning technology developed at Simon Fraser University. The DM was designed with attention to the key challenges that university students face in preparing well-reasoned arguments (Nesbit et al., 2019). They often ignore counterevidence, and they often fail to present and rebut counterarguments (Santos & Santos, 1999). When they do acknowledge counterarguments, they may resist argument-counterargument integration such as introducing pertinent qualifications to the thesis (Nussbaum & Schraw, 2007). Students also have difficulty judging the strength of evidence supporting claims and presenting the components of their argument in a coherent order. Inspired by its predecessor, the argumentation Vee diagram, the right half of the DM is dedicated to counterarguments and counterevidence. The three principles for designing cognitive tools are manifest in the design of the DM. The visual representation prompts students to construct balanced arguments that examine both sides of an issue. Students interact with the DM through several features designed around the key challenges we identified. They horizontally link related pro and con reasons and in so doing gain practice in argument-counterargument integration. The work of reorganising the order of the argument is partially distributed to the tool by a feature which allows students to move a claim (and any opposing claim linked to it) up or down to a new position. Each reason (pro or con) has a slider that students can adjust to represent the strength with which it supports or undermines the central thesis. When it is deployed in undergraduate biology classes, students who constructed arguments using the DM showed growth in the quality of their arguments over a series of three assignments (Niu, Sharp, & Nesbit, 2015).

Studying educational resources places extraordinary demands on university students because they must simultaneously fulfill the dual tasks of cognitively processing information in multiple resources while strategically self-regulating that processing as they strive to achieve learning goals. nStudy is a collection of web-based cognitive tools designed to scaffold metacognitive monitoring and self-regulated learning for learners studying text, writing essays, or engaged in other forms of text-based information problem-solving (Winne et al., 2017). In the upcoming version of nStudy, instructors will be able to create specialised templates that represent schemas they intend learners to acquire. The templates can include text fields and sliders, akin to the palettes and belief meter of Bioworld, which prompt learners to record in the template what they know or believe about a topic they are investigating. The templates students fill in make their understanding of a topic more self-evident and invite the self-regulatory processes of evaluating and revising learning strategies. To fully acquire the schema represented by a template, a student may need to thoughtfully activate and complete a template artefact multiple times and in a variety of contexts.

nStudy is currently being augmented with learning analytics designed to motivate and guide students towards productive self-regulated learning (Winne, 2017; Winne & Marzouk, 2019). Marzouk et al. (2016) described how learning analytics, beyond simply mirroring learners' behaviour, can visualise students' engagement with resources in ways that represent their learning strategies and foster their metacognition and motivation to learn. Goal setting is a crucial element of self-regulated learning. If students are able to set goals for studying by identifying materials they wish to study, the schedule they wish to follow, and the study tactics (e.g., tagging, note-taking) they wish to deploy, learning analytics can be configured to track and report to students their progress towards those goals. Seen as a cognitive tool for goal setting and goal fulfillment, the learning analytic described by Marzouk et al. exemplifies the three design principles of representation, interaction, and distributed cognition: Key concepts (resources, activities, schedule) and relationships among them are represented in the visualisation; the clerical task of gathering and aggregating trace data is distributed to the tool; and the students' repeated interactions with the tool are designed to help them internalise fundamental concepts and processes of self-regulated learning.

Because they can be operationally defined, the three attributes of representation, interactivity, and distributed cognition that characterise software-based cognitive tools also have a role to play in evaluating, iteratively redesigning, and researching the tools. Data gathered by means of log files, screen capture, eye tracking, and student products can be analysed to evaluate whether features of the tools are having their intended effects. To evaluate the interactivity of the DM interface, one could analyse screen captures and other trace data to determine whether, how often, and under which circumstances students are using the slider to estimate the strength of reasons. To evaluate distributed cognition, one could analyse eye-tracking data to investigate the extent to which students visually refer back to the DM as they search sources for evidence. To evaluate whether the representational structure of the DM has been internalised, one could look for its traces in the structure of essays students write later without the aid of the DM. Being derived from theory and amenable to operational definition, the three attributes we have described are suitable for guiding both hypotheses and methods in research on how cognitive tools can be designed to promote learning.

Acknowledgements

Support for this research was provided by a grant (435-2012-0723) from the Social Sciences and Humanities Research Council of Canada to John C. Nesbit.

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Please cite as: Pakdaman-Savoji, A., Nesbit, J. C., & Gajdamaschko, N. (2019). The conceptualisation of cognitive tools in learning and technology: A review. *Australasian Journal of Educational Technology, 35*(2), 1–24. https://doi.org/10.14742/ajet.4704

Appendix: Supplementary references list for systematic review

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