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ORIGINAL ARTICLE

Cognitive Aging and Computer-Based Instructional Design: Where Do We Go From Here?

Pascal W. M. Van Gerven · Fred Paas · Huib K. Tabbers

Abstract In this article, themost relevant literature on cognitive aging and instructional design is merged to formulate recommendations for designing computer-based training material aimed at elderly learners. The core message is that researchers and instructional designers do not need to develop special computerized instruction for older adults. Rather, existing principles of general instructional and multimedia design can be evaluated and used to accommodate the needs of elderly learners. Particular attention is given to John Sweller's Cognitive Load Theory (CLT) and Richard Mayer's Cognitive Theory of Multimedia Learning (CTML). It is argued that these instructional theories bear important benefits for older learners because they support an efficient use of available cognitive resources. New research directions are suggested to test the implications of these theories for learning in old age.

Keywords Cognitive aging · Instructional design · Complex skill learning · Cognitive load · Multimedia

The aim of this article is to survey the literature on how properly designed computerized instruction can support older adults in maximizing their capabilities to acquire new cognitive skills. Where studies on computer-based instructional design are abundant, research on their effectiveness for older adults still has a long way to go. Therefore, a second aim of this article is to generate research issues that start from the idea that existing theories of cognitive aging and instructional design constitute a solid basis for formulating guidelines to optimize

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performance of elderly learners. Before explaining this idea, however, we take a closer look at the most important phenomena associated with cognitive aging. Subsequently, these phenomena are linked to instructional strategies that can alleviate their negative impact on learning performance.

Phenomena of Cognitive Aging

When we speak of "cognitive aging," we usually refer to a decline of processes that contribute to the efficiency of information processing. Most of these declined processes can be rooted back to decreases in metabolic efficiency at the neural level (e.g., less effective signal transmission; see Hedden & Gabrieli, 2004, for an overview). Furthermore, there is a strong relation between age-related cognitive decline and reduced sensory ability that may have a common biological basis (Baltes & Lindenberger, 1997).

At the behavioral level, one of the most central age-related declines is a reduction of *general cognitive speed* (Fisk & Warr, 1996; Salthouse, 1996). This phenomenon affects every cognitive function at every level of processing. As a consequence, the cognitive system as a whole is dramatically slowed down. In most speeded cognitive tasks, there is a linear relationship between the reaction times of the young and the reaction times of the elderly, where the reaction times of the elderly are between 1.4 and 2.0 times slower than the reaction times of the young (see, e.g., Cerella, 1990). According to Salthouse (1996) general slowing is problematic in two respects. First, there is the "limited-time mechanism" which means that the more time is needed for early cognitive processes, the less time is left for later processes. This mechanism is especially problematic in tasks that involve time constraints. Second, there is the "simultaneity mechanism" which implies that results of earlier processes may have decayed below a certain threshold before later processes are finished. As a consequence, the outcomes of different sub-processes are not simultaneously active in working memory and cannot be combined for further processing. For example, if one is reading a long sentence and activation of the first words has decayed by the time one arrives at the end of the sentence, then it is hard to understand the sentence as a whole. Salthouse claims that declined cognitive speed is the most central mechanism of cognitive aging. This claim is based on findings from path model analyses, in which speed as a mediator between age and cognition explains a substantial part of the variance that is accounted for by age if speed is not included in the model (see Salthouse, 1993).

A second general decline involves *cognitive control* (e.g., Braver & Barch, 2002). Cognitive control entails a whole group of mechanisms aimed at manipulating information in working memory and at planning behavior. Impairments of cognitive control are usually associated with atrophy in the frontal lobes of the neocortex (e.g., Tisserand & Jolles, 2003). In the context of Baddeley's (1992, 2003) model of working memory, impairments of cognitive control are located in the "central executive." One of the most extensively studied control mechanisms is the inhibition of irrelevant information in working memory. The notion that a reduction of inhibitory control could underlie age-related memory decline was first put forward by Hasher and Zacks (1988). At that time, one of the most prevalent views of cognitive aging was that it primarily involves a reduction of the storage capacity of working memory. Hasher and Zacks' alternative view was that working memory tends to get overflowed by irrelevant information that is not effectively suppressed. Although this "inhibitory deficit view" has had its ups and downs in the past decade, it is still one of the major accounts of age-related performance impairments on a wide variety of cognitive tasks (see, e.g., Persad, Abeles, Zacks, & Denburg, 2002).

Not surprisingly, effective cognitive control takes more than inhibition alone. Mechanisms such as task switching, updating, searching, integration, coordination, and selection have been identified as separate cognitive control processes, most of which are affected by cognitive aging (see, e.g., Fisk & Sharp, 2004). One of these mechanisms—*coordination*—is particularly affected. Using figural transformation tasks, Mayr and collaborators (Mayr & Kliegl, 1993; Mayr, Kliegl, & Krampe, 1996) showed that age-related slowing is larger under "coordinatively complex" conditions than under "sequentially complex" conditions. Sequential complexity refers to any task manipulation that leads to a variation in the number of independent processing steps but does not increase the amount of information exchange between single steps. Coordinative complexity, on the other hand, refers to the amount of coordinative processing required to regulate and monitor the flow of information between interrelated processing steps.

By introducing the distinction between sequential and coordinative complexity, Mayr and Kliegl (1993) identified a moderator of the so-called "complexity effect": The phenomenon that age-related performance differences become larger as the task becomes more complex (see, e.g., Oberauer & Kliegl, 2001; Salthouse, 1992). That is, complexity effects emerge if a task is coordinatively, rather than sequentially, complex. The complexity effect is so general and robust that Perfect and Maylor (2000) consider it the null hypothesis—or "dull hypothesis," as they prefer to call it—in cognitive aging research. Conversely, the absence of a complexity effect is proposed as the alternative hypothesis. In other words, aging research should not be aimed at finding interactions between age and level of complexity. What is really worth pursuing is a rejection of this dull hypothesis.

Essentially, rejection of the dull hypothesis is what instructional design should also aim at. Although this may be too ambitious in many cases, a reduction of the complexity effect—that is, a reduction of the performance gap between young and old in complex task domains—should be an attainable goal. In the next section, a number of recommendations are surveyed that are specifically aimed at the instructional design needs of elderly learners. These recommendations are based on general findings extracted from cognitive aging research.

Instructional Design Needs of Elderly Learners

The aging brain shows an astonishing amount of plasticity and robustness by circumventing the effects of atrophy through the mobilization of alternative neural circuits (e.g., Daselaar & Cabeza, 2005). Furthermore, the brain appears to be protected against age-related performance impairments through favorable physical, social, and mental circumstances (e.g., Rowe & Kahn, 1987; Satz, 1993; Stern, 2002). Nevertheless, most aging people experience at least some of the aforementioned declines. At the same time, compensation of these declines by experience or expertise (i.e., crystallized abilities) is limited in that it is only attainable in specific, highly practiced task domains (e.g., Park, 1994).

Therefore, we start our survey with the assumption that "normally" aging individuals experience cognitive limitations that hamper their ability to acquire entirely new cognitive skills. The most obvious and well-documented skill in this respect is interacting with computers (e.g., Czaja, 1996; Czaja & Sharit, 1993). By now, computers have entered people's professional and private lives. Elderly people who did not yet catch up with this development are likely to encounter problems in adopting new software and computer technology (see Czaja & Sharit, 1998a). However, in this article, we do not discuss the reluctance of older individuals to use computers or the strategies that can be used to overcome their computer fear (see, e.g., Czaja & Sharit, 1998a; Morris, 1994). Our discussion is focused on those older adults that can be regarded as open-minded and eager to learn new skills, but who experience cognitive limitations as a result of the normal aging process.

Throughout the 1990s, researchers have studied performance of older adults on different kinds of computer tasks and identified the instructional needs of elderly people in mastering computer-based skills. Czaja and Sharit (1993), for instance, looked at performance of both young and elderly individuals (range: 25–70 years) on a data-entry, file-modification, and inventory-management task. These tasks differed in the number and type of decisions, the level of control, the degree of repetitiveness, and the level of complexity. Along these dimensions, the data-entry task was considered the most simple and repetitive, the inventory-management task the most complex and least structured, and the file-modification task moderately complex and structured. Furthermore, these tasks were administered under either a computer-paced or a self-paced condition. The results showed that the older participants were slower and made more errors on all tasks than their younger counterparts, but differences were greatest in the more demanding tasks. This pattern of results exemplifies a classical complexity effect. Furthermore, there was an interaction between age and pacing: Age-related performance differences were greater under the computer-paced condition than under the self-paced condition. Unsurprisingly, Czaja and Sharit found that experience with computers had the greatest effect on performance (see also Czaja, Sharit, Ownby, Roth, & Nair, 2001). In a later study, Czaja and Sharit (1998b) additionally found data-entry performance positively correlated with visuospatial and memory abilities.

An important lesson drawn from the studies by Czaja and coworkers is that instructional design—for example, different types of pacing—should be based on knowledge from fundamental cognitive aging research—for example, age-related slowing. With this starting point in mind, Czaja (1996), for example, recommends that new knowledge be built upon prior knowledge in order to construct an appropriate mental model of, for instance, a computer. However, care should be taken that the to-be-learned material is not literally mapped on to the existing knowledge. For example, new knowledge of computers can be linked to old knowledge of typewriters, but this parallel is limited. Conversely, Caplan and Schooler (1990) found that older adults are less able than young adults to use mental models in mastering a computer program. In fact, they found age differences to increase under a model-based training condition.

Another set of recommendations for the acquisition of computer skills by aging individuals comes from Morrell and Echt (1996), who start from knowledge of age effects on text comprehension, working memory, spatial ability, and perceptual speed. With respect to text comprehension and working memory, they conclude that the load on working memory should be made as low as possible by using simple language, avoiding the need to make inferences, and using the active rather than the passive voice. They also conclude that errors should be corrected as soon as possible to avoid interference with later presented information. With respect to perceptual speed, they promote the application of slower, or self-paced instructional formats. Elsewhere, these authors stress the importance of text appearance in instructional material (type face, font size, letter and line spacing, etc.; Morrell & Echt, 1997) and the use of illustrations (see Morrell & Park, 1993). Supplementary design guidelines are provided by Rogers and Fisk (2000), who address the usability of computer interfaces and other systems, and by Charness (2001), who stresses the communication needs of elderly learners.

In surveying the literature on computer use among the elderly, two features are striking. First, virtually all studies start from the *needs* of elderly people to properly interact with computers and other devices. Second, interacting with computers is considered as a goal, rather than a means to acquire new skills. We propose a new orientation. Instead of focusing on the needs of elderly people in acquiring computer skills, we contend that computers can be used as a *means* to implement *general*—that is, age-independent—theories of instructional design to enhance learning in virtually every field, including interacting with computers. It is remarkable that even the relatively recent reviews on the instructional design needs of elderly learners (e.g., Charness, 2001; Fisk & Rogers, 2002; Fisk, Rogers, Charness, Czaja, & Sharit, 2004; Rogers & Fisk, 2000) are not based on general theories of instructional design. Interesting in this respect is the proposition by Fisk et al. (2004) who state that "good design for older adults is usually good design for people of all ages" (p. 61). We would like to reverse this proposition: Good design for people of all ages is *especially* good design for older adults. In the following section, we substantiate this proposition by presenting design guidelines based on two general theories of instructional design and by showing that multimedia learning environments provide suitable tools for implementing these guidelines to optimally support elderly learners.

The Benefits of General Instructional Theories for Elderly Learners

This section focuses on two general instructional theories. The first is Cognitive Load Theory (CLT) developed by John Sweller and colleagues (Sweller, 1999; Sweller, Van Merriënboer, & Paas, 1998; Van Merriënboer & Sweller, 2005). The second is Richard Mayer's (2001) Cognitive Theory of Multimedia Learning (CTML). The former is not specifically aimed at computer-based learning environments; the latter is. The combination of the two theories yields a powerful tool for supporting skill acquisition in the elderly.

Both CLT and CTML are based on a cognitive architecture in which a capacity-limited working memory is connected to an unlimited long-term store. According to Baddeley (1992, 2003), working memory consists of two modality-specific stores. These so-called "slave systems"—the phonological loop and the visuospatial sketchpad—hold information for a limited amount of time. During this period, information is manipulated by a central executive and is transferred to the long-term store. This cognitive architecture bears an important constraint: Because working memory is limited in the amount of information it can handle and because it serves as a gate to long-term memory, it restricts the rate of learning. Limited processing capacity can be compensated in at least two ways, however. First, new information can be linked to prior knowledge in the long-term store, which accelerates the transfer of information to long-term memory (Ericsson & Kintsch, 1995). In novice learners, prior knowledge is not yet available, however. Therefore, a second strategy is to present information such that it is transferred to long-term memory in a highly efficient manner. This is exactly the aim of both CLT and CTML. The next subsection addresses the instructional design principles that follow from CLT.

Instructional design principles based on CLT

CLT handles the limited capacity of the modality-specific stores in working memory both by reducing *extraneous* or irrelevant cognitive load and by optimizing the level of *germane* or relevant cognitive load (see Paas, Tuovinen, Tabbers, & Van Gerven, 2003). Thus, the philosophy of CLT is not to merely reduce the load imposed on working memory, but to use working memory to its full extent. This dual strategy is especially helpful if (a) people do not yet possess domain-specific prior knowledge, (b) the complexity of the task is high (see, e.g., Leahy, Chandler, & Sweller, 2003), and (c) the capacity of working memory is particularly limited, such as in the elderly (Van Gerven, Paas, Van Merriënboer, & Schmidt, 2000). As we have seen, age differences increase with task complexity. Thus, the challenge for instructional designers is to reduce the performance gap between young and old learners engaged in complex tasks. We argue that a reduction of age differences is achieved by applying exactly the same instructional design principles already proven effective in young adults.

One of these potentially strong design principles is the manipulation of the goal specificity of practice problems. The idea is that practice problems with less specified or even unspecified goals reduce the load on working memory and lead to a more extensive exploration of the problem space which, in turn, leads to improved learning (see Burns & Vollmeyer, 2002; Sweller & Levine, 1982). Paas, Camp, and Rikers (2001) studied this *goal-free effect* in maze learning among young and old adults. They found that the presence of a specific goal in the learning phase of a computerized maze task interferes with the construction of a cognitive schema of the underlying spatial structure of the maze and disproportionately compromises the elderly's ability to navigate successfully through the maze in the test phase. Although young adults outperformed old participants under all conditions, age differences were much smaller under the goal-free condition.

Another powerful instructional strategy is the use of worked examples instead of conventional practice problems. Whereas conventional problems require learners to solve a range of practice problems, worked examples require them to study the same problems with their worked-out solutions. Although the latter activity may seem relatively passive, it has repeatedly led to better results than a conventional format (e.g., Paas, 1992; Pirolli & Anderson, 1985; Ward & Sweller, 1990; Zhu & Simon, 1987). CLT explains these findings by assuming that conventional problems elicit both forward (i.e., from problem state to main goal) and backward processing (i.e., from main goal to sub-goals), whereas worked examples only evoke forward processing. Backward processing, which is induced by "weak" solving strategies such as means-ends analysis, is associated with extraneous cognitive load because it does not lead to insight in the problem structure. Instead, backward processing focuses on reducing the difference between the current state and the goal state of a problem. Forward processing is associated with germane cognitive load because it focuses on problem states and the operators that lead to the main goal. Van Gerven, Paas, Van Merriënboer, and Schmidt (2002) found that worked examples were a more efficient training format than conventional practice problems, especially for the older participants.

This *worked-example effect* was replicated in a study where worked examples were presented in a multimedia format (Van Gerven, Paas, Van Merriënboer, Hendriks, & Schmidt, 2003; Van Gerven, Paas, Van Merriënboer, & Schmidt, 2006). A multimedia learning environment has the advantage of enabling instructional designers to present the learning material audiovisually. Audiovisual presentations are cognitively efficient in three respects. First, they prevent unnecessary visual search between mutually dependent, but physically separated information sources, such as a diagram and its caption. Second, they make use of both the visual and auditory component of working memory, thereby minimizing the chance of overloading either component. This advantage is also known as the *modality effect* (e.g., Kalyuga, Chandler, & Sweller, 1999; Leahy et al., 2003; Mousavi, Low, & Sweller, 1995; Tabbers, Martens, & Van Merriënboer, 2004; Tindall-Ford, Chandler, & Sweller, 1997). Third, audiovisual presentations enable information to be encoded both verbally and nonverbally, which leads to high-quality and durable knowledge (see Clark & Paivio, 1991; Paivio, 1986). For these reasons, both CLT and CTML embrace multimedia as an instructional tool. In the next subsection, CTML-based instructional design principles are discussed.

Instructional design principles based on CTML

Whereas CLT emphasizes the use of multimedia as a means to control cognitive load, CTML is more concerned with attentional aspects of learning. Still, these theories have a lot in common because CTML is based on three assumptions about human cognitive architecture (Mayer, 2001) that are essentially equivalent to the premises of CL First, there is the *dual channel assumption* (related to the work of Paivio, 1986) which states that people possess separate channels for processing visual and verbal information. Second, there is the *limited capacity assumption* which signifies that people can process a limited amount of information in each of these channels at a time. Last, there is the *active processing assumption* which holds that learning is a three-step process of (a) attending to incoming information, (b) organizing this information in coherent mental representations, and (c) integrating these mental representations with prior knowledge. The instructional guidelines derived from CTML were tested mainly in scientific and technological learning domains. Topics in these domains can be visualized relatively easily because they often involve concrete mechanical or other dynamic processes that can be divided into discrete steps. Each step can be accompanied by visual or auditory explanation. Examples are the working of a bicycle tire pump (Mayer & Anderson, 1992) and the formation of lightning (Mayer & Moreno, 1998). Below are the major effects drawn from this line of multimedia learning research (for a more exhaustive overview, see Mayer, 2005; Mayer & Moreno, 2003):

- The *segmentation* effect refers to improved learning if the learner can control the time spent studying each step, or "segment," of multimedia instruction (Mayer & Chandler, 2001; Mayer, Dow, & Mayer, 2003).
- The *pretraining effect* occurs if learning material is presented in a "parts-whole sequence" (Mayer & Chandler, 2001; Mayer, Mathias, & Wetzell, 2002; Mayer, Mautone, & Prothero, 2002). This is a procedure in which first the constituent parts (concepts, definitions, basic operations, etc.) of the learning material are presented and then their mutual relations. For example, in a multimedia instruction on the Pythagorean theorem, it would be important to first introduce the sides of a right-angled triangle (i.e., horizontal side, vertical side, hypotenuse) before visualizing their squares and, finally, showing that the squared hypotenuse equals the summed squares of the other two sides.
- The *coherence effect* is obtained if interesting, attention drawing, but redundant information, such as background music, is left out of the multimedia presentation (Mayer, Heiser, & Lonn, 2001; Moreno & Mayer, 2000).
- The *signaling effect* occurs if those parts of the pictorial material that are mentioned in the narration are highlighted (Kalyuga et al. 1999; Mautone & Mayer, 2001).
- The *redundancy effect* is obtained if visual material is accompanied by auditory commentary instead of both auditory and visually presented commentary (Kalyuga, Chandler, & Sweller, 2004; Mayer et al., 2001).
- The *spatial contiguity effect* is found if text is printed near the corresponding parts of a diagram so that visual search is minimized (e.g., Moreno & Mayer, 1999; Sweller & Chandler, 1994).
- The *temporal contiguity effect* is obtained if narration and diagrams are presented simultaneously rather than successively (e.g., Chandler & Sweller, 1992; Mayer, Moreno, Boire, & Vagge, 1999).

Table 1 Age-related cognitive declines and potential compensatory multimedia strategies (Extension of Paas, Van Gerven, & Tabbers, 2005)

Age-related cognitive decline	Compensatory multimedia strategy	Corresponding effect(s)
Reduced processing capacity	Bimodal (audiovisual) presentation	Modality effect[a]
	Worked examples instead of conventional practice problems	Worked-example effect[b]
	Goal-free instead of goal-specific practice problems	Goal-free effect[c]
	Presenting instruction in a parts-whole sequence	Pretraining effect
	Omitting redundant information	Coherence effect
		Redundancy effect
Reduced cognitive speed	Bimodal (audiovisual) presentation	Modality effect[a]
	Enhanced timing	Temporal contiguity effect
	Omitting redundant information	Coherence effect
	Presenting instruction in learner-controlled segments	Redundancy effect
		Segmentation effect
Reduced inhibition	Omitting redundant information	Coherence effect
		Redundancy effect
	Attentional support	Signaling effect
		Spatial contiguity
Reduced coordination and integration	Bimodal (audiovisual) presentation	Modality effect[a]
	Enhanced timing	Temporal contiguity effect
	Enhanced layout	Spatial contiguity effect
	Omitting redundant information	Coherence effect
	Presenting instruction in a parts-whole sequence	Redundancy effect
		Pretraining effect

[a] Tested by Van Gerven et al. (2003) and Van Gerven et al. (2006): Main effect of instruction.

[b] Tested by Van Gerven et al. (2002): Instruction × age interaction.

[c] Tested by Paas et al. (2001): Instruction × age interaction.

Why re-invent the wheel?

Up until now, few of the recommendations emerging from CLT and CTML have been tested with older learners. This is peculiar because they seem to accommodate the cognitive needs of the elderly. That is, they aim at an efficient use of working memory, the limits of which are particularly evident in old age (see Van Gerven et al., 2000). Therefore, our message is that instead of re-inventing the wheel by developing instruction based on the cognitive needs of older adults, researchers should look at the possible benefits of *existing* instructional theories for this group. Recently, Paas, Van Gerven, and Tabbers (2005) outlined the possible implications of CLT and CTML for elderly learners in multimedia-based learning environments. According to these authors, it is important to map systematically age-related cognitive declines on the potentially compensatory strategies offered by existing instructional theories. For that purpose, they formulated four groups of age-related cognitive declines: (a) Reduced processing capacity of working memory, (b) reduced cognitive speed, (c) reduced inhibition of irrelevant information, and (d) reduced coordination and integration of different information sources. Subsequently, they surveyed those CLT- or CTML-based instructional design principles that might compensate for each of these declines. An extended overview of this "mapping" approach is given in Table 1. All of the listed age-related declines in the first column of this table potentially can be compensated for by the existing design principles given in the second column. The effects corresponding to these design principles are listed in the table's third column. Of all these effects, only the modality effect, the worked-example effect, and the goal-free effect have been tested with elderly learners. Note that an interaction between instruction and age in Table 1 means that the elderly took more advantage of the instructional strategy than their younger counterparts. In the following section, the implications of the instructional design principles given in Table 1 are discussed in greater detail.

Mapping Effective Instructional Design Principles on the Cognitive Constraints of Older Learners

For a full understanding of Table 1, we discuss the guidelines produced by CLT and CTML according to the age-related cognitive declines that they might fit. To illustrate our points, we apply each of the guidelines to a worked example that was used in a study by Van Gerven et al. (2002). This worked example was used for teaching a basic strategy for solving the so-called "water-jug problem" (Luchins, 1942). The water-jug problem is somewhat contrived, but its complexity and abstraction level is comparable to that of an average math problem. Moreover, the water-jug problem has a limited problem space—that is, it involves a finite number of possible moves—which makes it relatively easy to quantify and is therefore commonly used for studying problem solving behavior (see, e.g., Atwood, Masson, & Polson, 1980). The display of the water-jug problem as used by Van Gerven et al. is shown in Fig. 1. The goal of the problem is to acquire a certain amount of water in a target jug. The target jug is shown at the bottom right of Fig. 1. The goal amount of water is indicated below the target jug. At the bottom left of Fig. 1, there are two so-called "working jugs" that have different capacities (indicated as "max." below the jugs). These working jugs can be filled with water by first touching the tap at the top left part of the display and then touching one of the working jugs which is then filled to the brim (it is not possible to tap less than the maximum amount of water). In this case, the right working jug is filled with five units of water. The target amount is

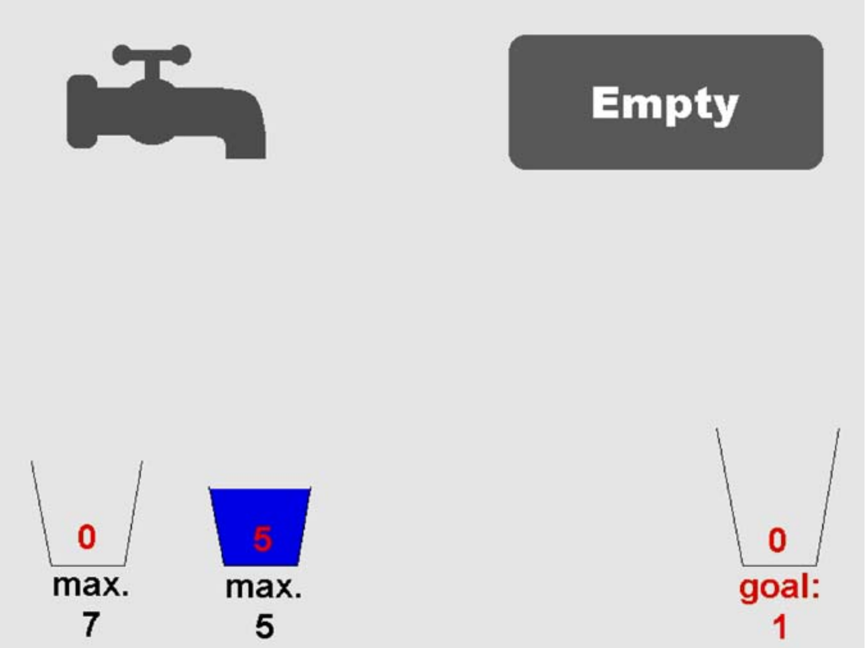

Fig. 1 Interface of the water-jug problem as it was used by Van Gerven et al. (2002)

one unit, however. Because none of the working jugs has a capacity of exactly one unit, the contents of the working jugs must be strategically poured into one another to arrive at this target quantity. This can be achieved by using the following rule: If the contents of a jug are poured into a jug that has an insufficient capacity, then a residual remains in the donating jug. This residual can be used for further operations.[1]

Van Gerven et al. (2002) trained young and older participants to use a number of basic strategies for solving the water-jug problem by presenting them with worked examples of the type shown in Fig. 2. In every worked example, one elementary strategy was explained in a step-by-step fashion. Every step was accompanied by a textual explanation. Steps appeared one at a time and the rate of presentation was controlled by the participant. We describe the guidelines presented in Table 1 in the light of the worked example shown in Fig. 2. Furthermore, we suggest variants of this worked example that make it more suitable for older learners.

To compensate for a reduced processing capacity of working memory, Table 1 provides five instructional strategies. First, there is bimodal presentation of instructional material which stimulates a more efficient use of working memory capacity by using two instead of one modality-specific slave systems. In the case of the worked example in Fig. 2, the text can be presented auditorily rather than visually (see Van Gerven et al., 2003). Relieving the

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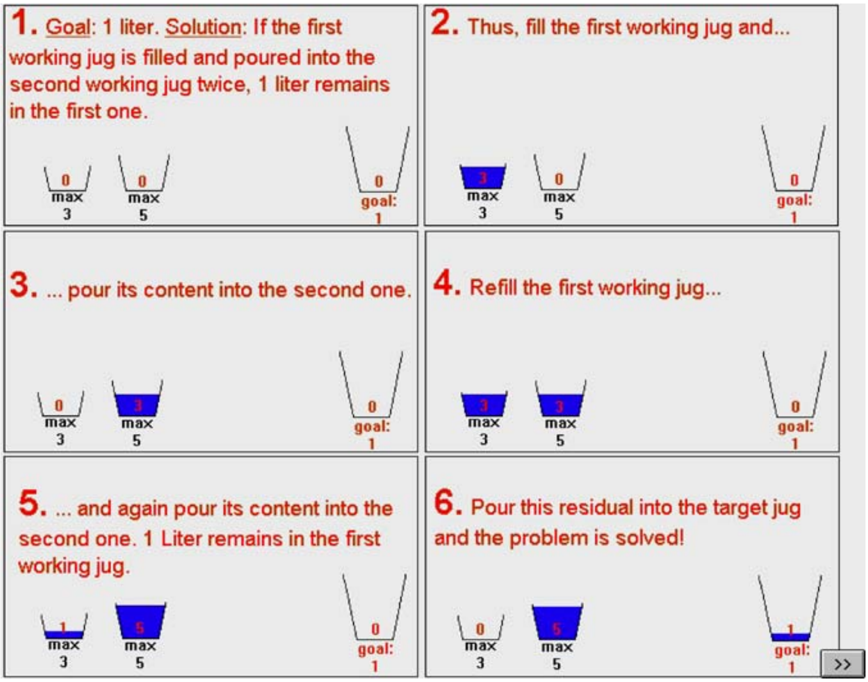
[1] Solution to the water-jug problem in Fig. 1: The five units of water in the right working jug are poured into the left working jug, which has a capacity of seven units and can thus receive two more units of water. If the right jug is refilled and poured into the left jug, three units remain in the right jug. These three units are poured into the left jug after the left jug is emptied. Thus, the left jug can contain four more units of water. If the right jug is refilled with five units and is then poured into the left jug, one unit remains in the right jug. This is exactly the required amount of water which is subsequently poured into the target jug.

visual system is especially beneficial for the elderly because of age-related capacity limits. A second strategy to compensate for reduced processing capacity is the use of worked examples instead of conventional practice problems. Worked examples reduce extraneous activity in working memory which again is especially beneficial for older learners. Presenting a water-jug problem in the format shown in Fig. 2 is more effective than presenting a problem in the format shown in Fig. 1 because the latter induces a capacity demanding means-ends strategy, whereas the former efficiently draws attention to problem states and operations to progress toward a solution. The same cognitive benefit results from the third strategy: The application of goal-free problems. Although every problem has a goal state, the attention of the learner should not be primarily focused on this goal state. Instead, the learner's attention should be aimed at the different problem states and the appropriate actions to reach a solution. In the case of the water-jug problem, the goal statement "acquire 1 unit of water" might be replaced by the statement "acquire as many different quantities of water (between 1 and 10 units) as you can." Where the former leads to a means-ends strategy, the latter stimulates a more elaborate exploration of the problem and leads to better test performance (cf. Paas et al., 2001). A fourth strategy is the presentation of the instructional material in a parts-whole sequence. Presenting the elementary parts of the subject matter first and then the interactions between these parts minimizes working memory load in the earlier stages of learning and maximizes the chance of correctly combining these parts at a later stage (see the earlier mentioned example on the Pythagorean theorem). In the case of the water-jug problem, the basic strategies might be explained first, as in Fig. 2. Subsequently, one might show how a combination of these strategies can be used to solve more complex problems. A fifth strategy is omitting redundant information. This maximizes the cognitive capacity available for relevant processing. Thus, if the text in Fig. 2 is presented auditorily as well as visually, then either the spoken text or the on-screen text is superfluous and should be omitted.

Reduced cognitive speed can be compensated for by preventing the simultaneity mechanism (i.e., corresponding information elements might not be simultaneously available in working memory; Salthouse, 1996). Bimodal presentation stimulates the integration of pictorial and verbal information. Integration of these information sources can be optimized by enhanced timing. For example, in the worked example depicted in Fig. 2, it is important that the appearance of the visual and verbal information in each step occurs simultaneously rather than serially. A further strategy to compensate for reduced cognitive speed is omitting redundant information (e.g., visual text if the verbal material is presented auditorily). In this way, the learner is prevented from taking extra mental processing steps that increase the chance of information decay. Finally, by making the instructional material self-paced, the learner can adjust the presentation rate to a preferred speed. Thus, every step in Fig. 2 should become available at the learner's request.

Reduced inhibition can be controlled by omitting redundant information from instruction. Multimedia presentations are commonly adorned with attractive, but distracting, elements such as background music, moving logos, commercial banners, reminders, and unasked-for help dialogues. Especially for elderly people, these additions are potentially harmful to the learning process because they increase the chance of irrelevant information being processed in working memory. Although it might seem a good idea to make the presentation of the water-jug problem more attractive or realistic by adding all kinds of "bells and whistles," like the sound of streaming water, such additions are likely to diminish learning. Apart from omitting irrelevant stimuli, attention can also be supported by highlighting relevant parts of the presentation. In addition, the spatial layout of the learning material can be improved by grouping related parts of information. Both the strategies prevent unnecessary visual search and thus minimize the probability of attending to irrelevant information. Thus, in Fig. 2, for



1. Goal: 1 liter. Solution: If the first working jug is filled and poured into the second working jug twice, 1 liter remains in the first one.

2. Thus, fill the first working jug and...

3. ... pour its content into the second one.

4. Refill the first working jug...

5. ... and again pour its content into the second one. 1 Liter remains in the first working jug.

6. Pour this residual into the target jug and the problem is solved!

Fig. 2 Worked example of a basic strategy to solve a water-jug problem

example, the working jug at the bottom left part of the display might be highlighted when it is mentioned in the text as “the first working jug.” The same principle can be applied to the other jug when it is referred to as “the second one,” and so on.

Reduced coordination and integration, finally, can be compensated for by bimodal presentation which facilitates integration of visual and verbal information. Enhanced timing of visual and auditory information is essential because it determines the simultaneous availability of these sources. In addition, the spatial layout of the material might support information integration by grouping related elements and separating unrelated elements. If visual text is used, as in Fig. 2, it could be presented close to the corresponding parts of the display, for example, by using text balloons. Furthermore, omission of redundant information prevents the learner from incorporating irrelevant elements into previously stored knowledge. Finally, organizing the learning material into a parts-whole sequence helps elderly learners integrate the different parts of the learning material in an effective step-by-step way.

Where Do We Go from here?

The previous section showed that existing instructional theories can likely enhance learning for older adults. An important theoretical question to be answered is whether there is enough reason to expect that older learners take *more* advantage of enhanced computer-based instruction than their younger counterparts. Such a disproportionate advantage would imply an interaction between instruction type (conventional versus enhanced) and age (young versus old), where age differences are smaller under the enhanced than under the conventional condition. The literature is mixed about this interaction. Some studies found a main effect for instruction type; others found an interaction between instruction type and age. Charness, Kelley, Bosman, and Mottram (2001), for example, did not find a disproportionate advantage in older compared to younger adults when testing a multi-day training procedure for learning word-processing skills. In a CLT context, Van Gerven et al. (2003) did not find a greater advantageous effect of multimedia training for older compared to younger adults. On the other hand, Van Gerven et al. (2002) did find an instruction type by age interaction when instruction involved a worked-examples group and a conventional-practice group. Paas et al. (2001) found a similar interaction when comparing a goal-free with a goal-specific group. These mixed results indicate that reducing the performance gap between young and older learners is a possible, but not a definite, result. The occurrence of an interaction may depend on the strength of the instructional manipulation, the characteristics of the skill to be mastered, and the expertise of the learner (see, e.g., Czaja et al., 2001).

From a theoretical basis, however, there is reason to expect an instruction by age interaction. Van Gerven et al. (2000), for instance, argue that the elderly have more room to improve their performance than younger adults. At the same time, younger adults need less support than older adults. Therefore, Van Gerven et al. hypothesized a greater advantage of enhanced multimedia instruction for older than for younger learners. Moreover, Craik (1986) pointed out that memory performance of older adults depends on external support of mental operations (e.g., cues) because they are less able than younger adults to initiate these operations by themselves. It is for this reason that age differences are smaller when testing is cued versus uncued. Although CLT and CTML focus on the input level (i.e., effective instruction) and Craik at the output level (i.e., effective retrieval), both input and output approaches support relevant mental operations. Therefore, we believe that reducing the age-related performance gap is not only a noble ambition, but also a compelling hypothesis.

Besides testing the design principles presented in Table 1, educational gerontology faces another challenge. As we have shown, most instructional design principles are aimed at the reduction of cognitive load. However, learning complex skills can only take place if learning material is processed actively and transformed into cognitive schemata. Thus, it is important to stimulate a maximal use of *available*—including released—cognitive capacity. In terms of CLT, this means that germane cognitive load must be set to an optimal level.

Computers can play an important role in optimizing the level of germane cognitive load. For example, practice problem difficulty can be adjusted on the basis of performance on preceding practice problems. That is, a computer program can keep track of individual levels of cognitive load and performance so that training complexity can be adjusted to the current proficiency of the learner (Camp, Paas, Rikers, & Van Merriënboer, 2001; Salden, Paas, Broers, & Van Merriënboer, 2004). Thus, individual sequences of training problems can be produced that impose optimal levels of germane cognitive load. Again, this would be especially helpful to elderly learners because cognitive overload is avoided and available resources are maximally employed.

Computers can also optimize germane cognitive load by controlling training variability (see Paas & Van Merrienboer, 1994). Increased training variability prevents the learner from processing practice problems superficially. That is, when confronted with a sequence of relatively unrelated training problems, the learner is compelled to reanalyze every new problem which results in more meaningful processing. Increased training variability has yielded positive results with elderly learners (Jamieson & Rogers, 2000; Van Gerven et al., 2006). Finally, controlling the goal specificity of training problems might also optimize germane cognitive load because a reduction of goal specificity stimulates a more extensive exploration of the problem space (see Paas et al., 2001).

To conclude, our literature review shows that the key to optimal learning in the elderly might be surprisingly near at hand. Computers can support learning performance of older adults in at least two ways. First, they can manage the level of extraneous cognitive load by controlling the training format (e.g., modality). Second, they can control the level of germane cognitive load by determining the sequencing and goal specificity of training problems. The combination of these control opportunities should lead to improved learning in older adults without having to invest time and effort in the development of "age-specific" instructional formats.

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