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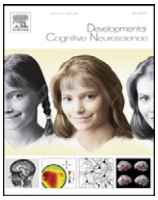

The two-component model of memory development, and its potential implications for educational settings

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ABSTRACT

We recently introduced a two-component model of the mechanisms underlying age differences in memory functioning across the lifespan. According to this model, memory performance is based on associative and strategic components. The associative component is relatively mature by middle childhood, whereas the strategic component shows a maturational lag and continues to develop until young adulthood. Focusing on work from our own lab, we review studies from the domains of episodic and working memory informed by this model, and discuss their potential implications for educational settings. The episodic memory studies uncover the latent potential of the associative component in childhood by documenting children's ability to greatly improve their memory performance following mnemonic instruction and training. The studies on working memory also point to an immature strategic component in children whose operation is enhanced under supportive conditions. Educational settings may aim at fostering the interplay between associative and strategic components. We explore possible routes towards this goal by linking our findings to recent trends in research on instructional design.

1. Introduction

Cognitive capacities required for learning new associations depend on the interactions of neural networks that mature and develop across the lifespan. The encoding, retention, and retrieval of events and facts form the basis for acquiring new skills and knowledge. Hence, investigating the mechanisms and modifiability of learning and memory may yield insights that are relevant for educational practice.

This review is focused on developmental changes in memory functions from middle childhood up to old age. For reasons introduced below, middle childhood is a period in development in which environmental support provided by educational settings may have particularly large and beneficial effects on memory performance. With regard to adulthood, lifelong learning is required for independent living in modern knowledge-based societies (e.g., Schmiedek et al., 2010). Senescence-related decline in various sensory and cognitive functions poses challenges on the ability to acquire new skills and knowledge. Accordingly, age-, and even person-adapted learning environments may be required to foster information and technology transfer at all ages. In the following, we present evidence from our own research to highlight the strengths and weaknesses of learning and memory across the lifespan, and explore potential links to theories of instructional design (Mayer, 2005; Sweller et al., 1998).

Similar to others (D'Esposito, 2007; Fuster, 2003; McIntosh, 2000; Postle, 2006; Zimmer, 2008), we conceive of memory as an emergent property based on interactions in a distributed neural network that involves occipital,

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temporal, parietal and frontal brain regions. Age-comparative evidence from structural and functional magnetic resonance imaging (s/fMRI) suggests that the development of the underlying neural network is nonlinear and heterochronic throughout the lifepan: posterior brain regions such as occipital and mediotemporal cortices mature relatively early, whereas prefrontal brain regions show a maturational lag and continue in structural and functional growth until young adulthood (Giedd et al., 1999; Gogtay et al., 2004; Ofen et al., 2007; Sowell et al., 1999; but see Ghetti et al., 2010). In later adulthood, prefrontal regions are the first to show age-related decline. But also medio-temporal structures, and here especially the hippocampus, are vulnerable to senescent decline (e.g., Raz et al., 2005) that is even accelerated under pathological conditions (e.g., Small et al., 2011). How exactly these changes in neural structures relate to behavioral changes in learning and memory still remains to be clarified.

Our group recently proposed a two-component framework of memory that attempts to integrate behavioral and neural evidence on memory performance from a lifespan perspective (Sander et al., submitted for publication; Shing and Lindenberger, 2011; Shing et al., 2010), based on established theories and concepts (cf. Eichenbaum, 2002; Moscovitch, 1992; O'Reilly and Norman, 2002; Prull et al., 2000; Simons and Spiers, 2003). Our framework is motivated by the empirical observation that memory functions such as episodic memory and working memory show an improvement across childhood, a peak in young adulthood, and a marked decline with advancing age (Cowan et al., 2006; Gathercole, 1999; Luciana et al., 2005; Park and Payer, 2006; Schneider and Pressley, 1997; Singer et al., 2003). Despite the apparent symmetry in behavioral performance at the two ends of ontogeny, lifespan theory postulates that the mechanisms of maturation and senescence are not the same (Baltes et al., 2006; Craik and Bialystok, 2006). Accordingly, our work over the past years has aimed at identifying commonalities and dissimilarities in maturation and senescence of the cognitive and neural mechanisms underlying episodic and working memory performance across the lifespan.

Central to our framework is the assumption that memory relies on the successful combination of two distinct but intertwined processing components, one associative and the other strategic (Sander et al., submitted for publication; Shing and Lindenberger, 2011; Shing et al., 2008, 2010; see also Werkle-Bergner et al., 2006). The associative component refers to mechanisms during encoding, maintenance, and retrieval that integrate the features of a given mnemonic event into a coherent memory trace that is binding (Murre et al., 2006; Treisman, 1996). Binding processes occur at different levels of information processing (see e.g., Zimmer et al., 2006, for an elaboration on levels of binding and possible mechanisms). Neurally, the functions of the associative component are primarily dependent on the integrity of mediotemporal (MTL) and posterior brain regions (e.g., Simons and Spiers, 2003). Given the comparably faster developmental gains in measures of structural integrity for mediotemporal and posterior brain regions (Gogtay et al., 2004; Sowell et al., 2003, 2004), the associative component is thought to be relatively mature by middle childhood. In contrast, senescence-related decrements in hippocampal integrity (e.g., Raz et al., 2005) render the associative component vulnerable to age-related impairments (e.g., Naveh-Benjamin, 2000). In contrast, the strategic component refers to top-down control processes involved in the organization and monitoring of memory representations and mainly relies on prefrontal brain regions (PFC; Miller and Cohen, 2001). Given the protracted maturation of PFC, the strategic component is not yet fully functional by middle childhood, and develops across adolescence until young adulthood. Nevertheless, structural measures reveal early losses in PFC integrity with advancing adult age (e.g., Raz et al., 2005). Accordingly, decrements in PFC-dependent functions are hypothesized as a major source for age-related performance decrements during adulthood (e.g., Park and Reuter-Lorenz, 2009).

In general, the associative and strategic components are not thought to operate orthogonally. Rather, mnemonic functions generally require the successful recruitment of both associative and strategic processing mechanisms. Accordingly, the reliance on either of the two components across developmental time is conceptualized in relative terms. For example, although the associative component is assumed to be relatively mature by middle childhood, we would not preclude ongoing maturational processes (e.g., Ghetti et al., 2010) that may even be expedited by successfully practicing the combined use of strategic and associative components (e.g., Menon et al., 2005). At the same time, both children and older adults exhibit persistent difficulties when cognitive control demands are high (e.g., Sander et al., 2011a, 2012), rendering interventions targeting the strategic component useful to uncover the upper limits of performance potential at both ends of the lifespan (e.g., Brehmer et al., 2007; Shing et al., 2008).

The two-component model of memory development was originally introduced to study episodic memory development (e.g., Shing et al., 2008) but has recently been extended to working memory functioning (Sander et al., 2011a,b, 2012, submitted for publication). In the following, we will summarize work from both domains. We will report evidence suggesting that children's lower memory performance as compared to young adults is indeed related to the relative immaturity of strategic operations. At the same time, it will become clear that children's initial difficulties in strategic processing can be overcome by environmental settings that are conducive to a more efficient combination of strategic and associative components. We will also report evidence demonstrating that individual differences in memory development are enormous. Finally, we will outline possible implications of our work for educational settings.

2. Episodic memory functioning

One line of experiments from our group used instruction and training to investigate age-related differences in component processes supporting episodic memory functioning. Episodic memory (Tulving, 1972) refers to the explicit remembering of specific events that are situated in time and place (e.g., episodes). In order to form such an integrated memory representation that combines several sensory inputs (e.g., touch, smell, vision, sound) with stored prior knowledge, episodic memory mechanisms are crucially dependent on the associative mechanisms of the MTL (Simons and Spiers, 2003). Furthermore, episodic memories can be retrieved consciously and purposely (e.g., Rugg and Wilding, 2000; Tulving, 1972). The ability to form integrated memory traces for events situated in time and place is instrumental for the acquisition of knowledge about the self and the world (Tulving, 2002).

For the present review, we describe two multiphase training studies that investigated differences in episodic memory function in lifespan samples of children aged 9–12 years, younger adults, and older adults. In both studies, participants were first given an initial assessment of memory performance, followed by instruction in a highly effective mnemonic technique, and they were finally trained extensively on applying the technique. Both studies followed the logic of testing-the-limits paradigms (e.g., Lindenberger and Baltes, 1995): with such procedures, researchers try to approximate upper limits of performance potential with extensive practice and/or individually adjusted difficulty levels. For the two studies discussed below, extensive practice in elaborated mnemonic techniques was used to equate pre-experimentally existing differences in the spontaneous ability to recruit memory strategies. After participants had reached proficiency in the use of the strategies, the remaining age-group differences were assumed to be mainly driven by variability in other processing mechanisms, i.e., the associative component.

In the first study, Brehmer et al. (2007) investigated the extent to which memory performance can be improved by instruction and training in a total of 108 participants including younger children aged 9–10 years, older children aged 11–12 years, younger adults aged 20–25 years, and older adults aged 65–78 years. Participants learned and subsequently practiced an imagery-based mnemonic technique (Method of Loci) that emphasized the generation of interactive, dynamic images or thoughts to associate a given location cue with an auditorily presented word. In multiple trials, the participant's task was to memorize lists with 16 location-word pairs during encoding. Each encoding phase was followed by a cued-recall test, in which the locations served as cues for the associated words. During the strategy-practice phase, the encoding time was adjusted individually so that all individuals practiced the strategy at comparable levels of difficulty (towards a fixed criterion of ~60% correct recall). Practice lasted for two to six sessions, depending on the number of sessions needed for each of the participants' performance to reach a stable asymptote.

The main finding of this study is that both groups of children and older adults did not differ in performance level at baseline and directly after strategy instruction, but that children's performance improved substantially more than older adults' after the extensive practice phase (see Fig. 1a). The data was generally consistent with the assumption that children and teenagers profit from learning a memory strategy. The extensive and individualized period of practice presumably allowed children to overlearn the use of the strategy, bringing the latent potential of their well-established associative component to the fore. In addition to mean age differences in memory performance, substantial interindividual differences were observed from the dynamically adjusted practice phase, particularly in younger children. For example, the encoding times needed by each of the children to reach a performance criterion of 62.5% correct responses ranged from 1 s to 7.2 s (see Fig. 2a in Brehmer et al., 2007).

In a subsequent study, Shing et al. (2008) examined lifespan age differences in a verbal pair-recognition paradigm in which both strategic and associative demands were manipulated within person. Children (10–12 years), teenagers (13–15 years), younger adults (20–25 years), and older adults (70–75 years) participated in the study. The strategic component was varied by giving participants encoding instructions that emphasized remembering the single items of the word pair, the exact pairing, or the pairing through an instructed elaborated imagery strategy. The associative demand was varied by using word pairs in which both words were familiar to the participants (German–German, GG) or word pairs in which one of the two words was the exact translation in a foreign language (German–Malay, GM). By this, the GM-condition resembles vocabulary learning. GM pairs were assumed to increase the associative binding demands of the task as Malay was a completely unknown language for the German speaking participants.

Developmental differences between children and teenagers were especially pronounced for the GG condition (see Fig. 1b): teenagers and younger adults improved their performance substantially by simply being instructed to encode the words as a pair, apparently making use of self-initiated associative elaborations. Children and older adults did not profit from the mere pair instruction to the same extent as did teenagers and younger adults. However, children improved more from being instructed in using an imagery strategy than did the older adults.

Learning GM word pairs was more difficult than GG word pairs for all age groups and showed smaller improvements due to instruction (see Fig. 1c). In a follow-up experiment, participants were further trained on using the imagery strategy for GM word pairs in five sessions. Participants' performance was boosted by the extensive practice period. In particular, children and teenagers improved their performance as a function of strategy practice, with children achieving similar levels of performance as the teenagers (see Fig. 1c, the rightmost data points for each group).

The interaction between processes related to learning and maturation was further investigated in a follow-up study conducted by Brehmer et al. (2008). This study tested long-term maintenance (11 months after training) of a previously acquired method of loci memory strategy (Brehmer et al., 2007). Performance was tested without and after mnemonic reinstruction, indicating spontaneous versus reactive maintenance, respectively. Children showed reliable spontaneous performance improvements relative to the levels attained 11 months before, and did not show reliable additional gains from renewed instruction. This finding suggests that children did not need the instruction to reactivate their memory skills and to improve their

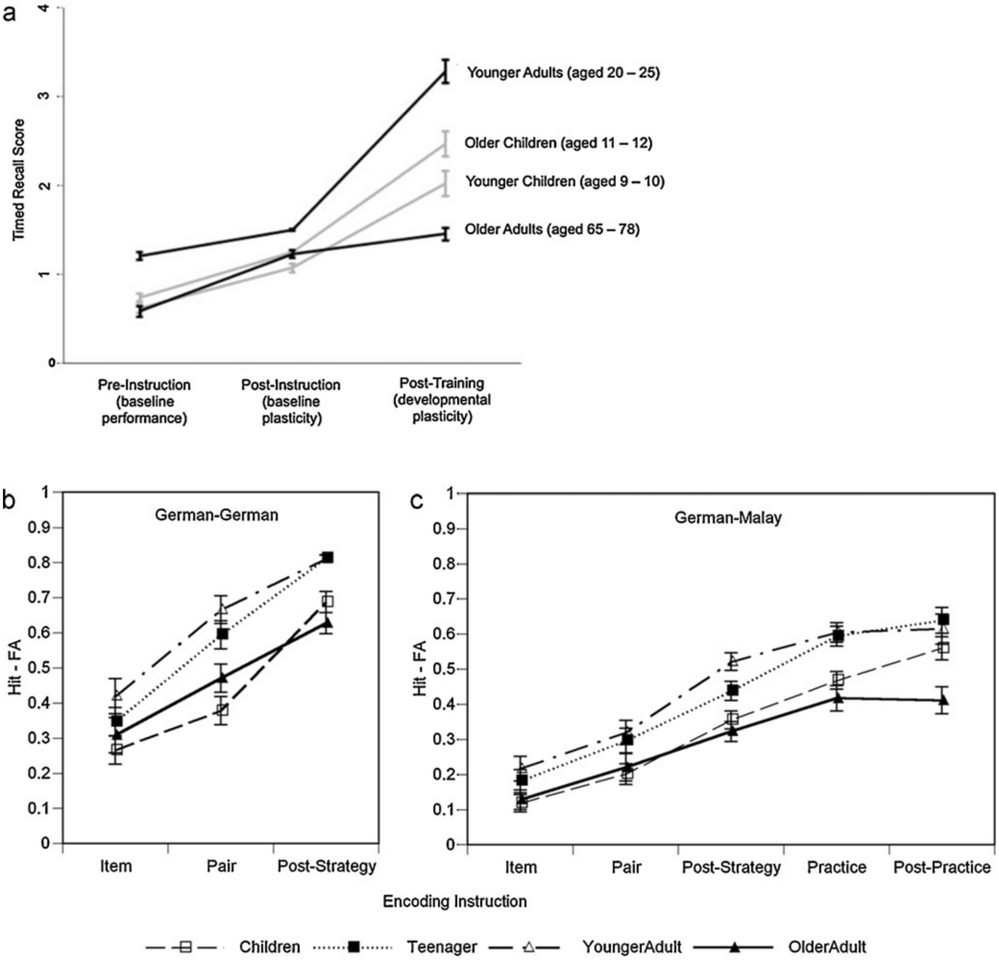

Fig. 1. Empirical support for the two-component framework of memory development across the lifespan from the episodic memory domain. (a) Children's memory performance improves substantially after strategy instruction and extensive practice, revealing the latent potential of their associative component. Adapted from Brehmer et al. (2007). (b) Children's memory performance for associatively less demanding German–German and (c) associatively demanding German–Malay word pairs improves after strategy instruction and practice. The need for instruction and practice interacts with the associative demands of the material. Adapted from Shing et al. (2008).

performance over time, possibly reflecting the maturation of the neural memory network supporting the strategic component of episodic memory.

To conclude, the two studies (Brehmer et al., 2007; Shing et al., 2008) indicate that the associative component of episodic memory is well developed in children and teenagers, and can be used in a highly effective manner when appropriate strategic instructions and training are provided. The amount of performance potential appears to depend on environmental and person-specific factors. For example, the observed differences between the conditions of German–German and German–Malay word pairs in the study by Shing et al. (2008) show that the needs for instruction, strategy supply, and training interact with the associative demands of the to-be-learned materials. In the same vein, the study by Brehmer et al. (2007) demonstrates that the amount of environmental support needed differs by age, and varies from person to person within a given age segment (cf. Craik and Jennings, 1992).

3. Working memory functioning

Another line of experiments conducted by our group extended the two component model of memory development by investigating commonalities and differences in mechanisms of working memory functioning across the lifespan. Working memory (WM) refers to our ability to briefly maintain and manipulate information in order to guide goal-directed behavior (D'Esposito, 2007). Its development during childhood is closely related to the development of cognitive control and fluid intelligence (Bunge et al., 2002; cf. Chapman and Lindenberger, 1989).

Although there is a wealth of literature on cognitive WM theories (e.g., Baddeley, 1986; Barrouillet et al., 2004; Cowan, 1995), our research is mainly inspired by neuroscientific views on WM functioning. According to these lines of evidence, WM can be understood as a set of information processing mechanisms that operate on representations maintained and transformed in distributed neuronal

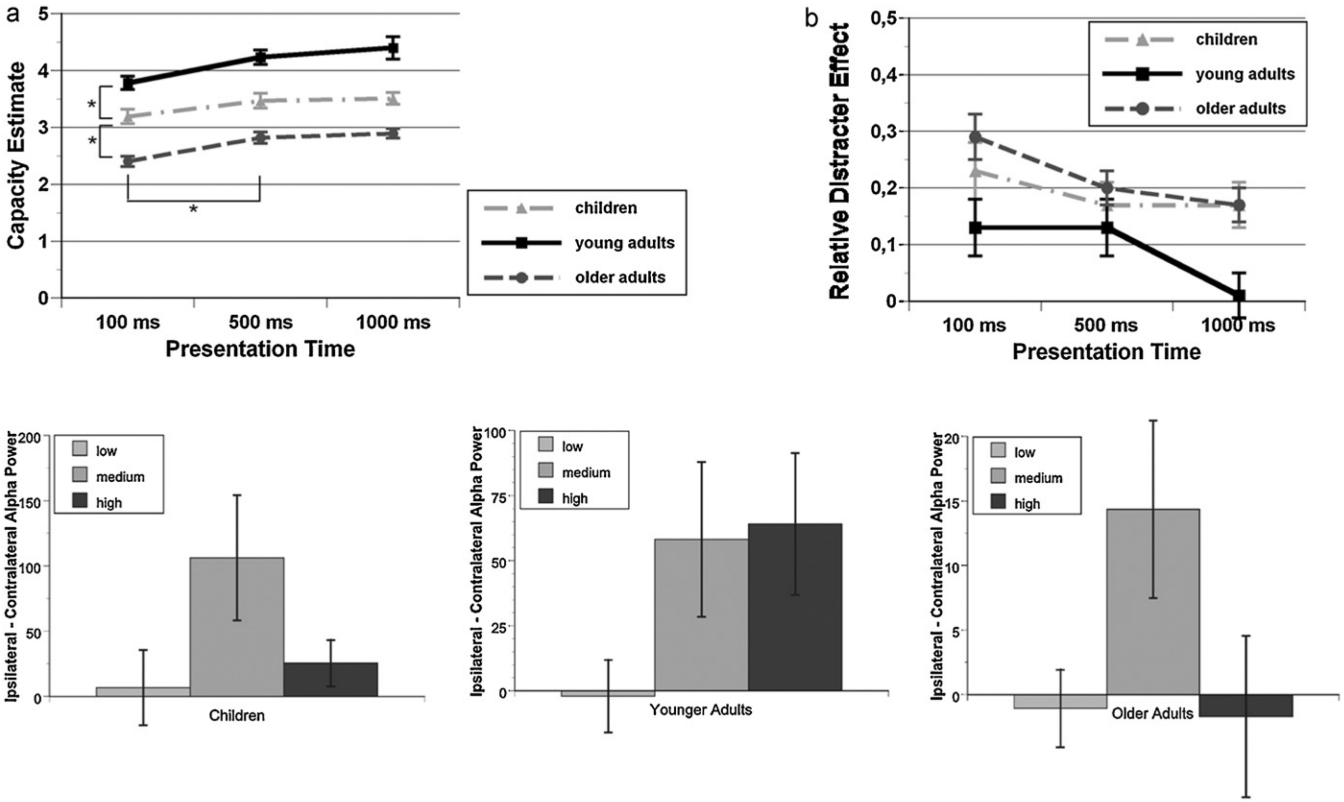

Fig. 2. Empirical support for the two-component framework of memory development across the lifespan from the working memory domain. (a) Children improve their performance with longer presentation times suggesting an enforcement of top-down control over visual input. (b) Longer presentation times reduce distracter effects in children, although limits in the efficient suppression of distracting information persist with long presentation times. Adapted from Sander et al. (2011a). (c) Children engage similar inhibitory neural mechanisms as young adults as indicated by load modulations of lateralized alpha power. However, inhibitory processes seem less robust when working memory load is high. Adapted from Sander et al. (2012).

networks (e.g., D'Esposito, 2007; Postle, 2006; Zimmer, 2008). Most crucially, the structural and functional networks supporting WM mechanisms in the brain strongly overlap with the networks viewed as critical for episodic memory functioning (Ranganath, 2006; Ranganath and Blumenfeld, 2005; Ranganath et al., 2005). Accordingly, one line of studies in our lab set out to probe the usability of the two-component framework of memory to explain lifespan age differences within the domain of WM (Sander et al., 2011a,b, 2012).

In the first study, Sander et al. (2011a) used a change-detection paradigm (Luck and Vogel, 1997), a variant of a delayed matching-to-sample task, to investigate the development of component processes contributing to WM capacity limits. In a change-detection paradigm, the participant is initially presented briefly with a memory array containing a variable number of items, such as colored squares. After a retention interval of about one second, a probe array is presented and the participant has to indicate via button press whether one of the items has changed or whether no change has occurred.

In line with prior research (Cowan et al., 2006; Riggs et al., 2006), we observed that children (10–12 years) and older adults (70–75 years) generally performed less well than young adults on this task. To disentangle the mechanisms that underlie the lower WM performance in children and older adults, we varied the presentation time of the memory display and presented variable numbers of items (2–10) for either 100 ms, 500 ms or 1000 ms. We assumed that under conditions of short presentation time, performance primarily relies on fast-acting feature binding mechanisms (e.g., Zimmer et al., 2006), that is, the associative component. In contrast, longer presentation times would lead to relying increasingly on more time-consuming control processes that stabilize early representations (e.g., Gazzaley et al., 2008). In line with these assumptions, our results demonstrated that all age groups were able to improve their performance with longer presentation times, suggesting that they were generally able to enforce top-down control over visual input when provided with sufficient time to successfully form integrated representations. Nevertheless, older adults' performance lagged children's in all time conditions, especially under conditions of a very short presentation time (i.e., 100 ms). This observation is in accordance with the proposition that the associative component of children is relatively functional while it is impaired in older adults (see Fig. 2a).

In a second experiment within the same study (Sander et al., 2011a) top-down control demands were increased by presenting distracters at the same time as targets at encoding and retrieval. This experiment was specifically designed to reveal constraints in the strategic processing component. Again all age groups improved their performance with longer presentation times, but distracter effects were larger in the children and older adults than in the young adults and persisted with long presentation times. Thus, children and older adults were generally able to use top-down control operations, or the strategic component of working memory. However, the persisting distracter effects under challenging task conditions revealed the efficiency limits of strategic control operations in children and older adults (see Fig. 2b). Nevertheless, performance in the children and older adults improved greatly when task structures were adapted to accommodate for less efficient control mechanisms, i.e., if they were given more time (Fig. 2b).

The behavioral evidence presented above is corroborated by electrophysiological data. In a recent study (Sander et al., 2011b), we investigated the contralateral delay activity (CDA), an event-related neurophysiological marker of WM functioning (e.g., Vogel and Machizawa, 2004; Vogel et al., 2005). The CDA is typically assessed with a cued version of the change-detection task. In this variant, the presentation of the memory array is preceded by a cue that instructs the participants to covertly shift their attention to the left or right visual hemifield. Furthermore, the participants are instructed to memorize only the items in the cued hemifield, while those in the uncued hemifield serve as distracters. The CDA is calculated as the difference between EEG responses from sensors over the contralateral hemisphere minus activity over the ipsilateral hemisphere with regard to cue direction. Typically, the CDA increases in amplitude with increasing WM load and reaches an asymptote around the capacity limit (e.g., Vogel et al., 2005).

The results of our study revealed age differential patterns of load-dependent CDA modulations with varying presentation time. Comparing the CDA amplitudes of conditions with 2 versus 4 items, the electrophysiological data indicate that the children were able to boost their performance presumably by engaging top-down control with long (500 ms), but not with short presentation times (100 ms). In contrast, younger adults showed signatures of top-down control with short presentation time, but made less use of strategic control with the long presentation time, presumably because this condition was so easy for them that they did not need to rely on it.

In further analyses we investigated an electrophysiological marker of inhibitory control processes within the same cued change-detection paradigm (Sander et al., 2012), namely, the power of neuronal oscillations in the alpha frequency range (i.e., 7–13 Hz). Oscillatory activity in this range provides a mechanism for the regulation of cortical excitation and inhibition in the service of neural information processing (e.g., Jensen and Mazaheri, 2010; Klimesch et al., 2007). Lateralization of posterior alpha power in change detection tasks has previously been shown to reflect the inhibition of task-irrelevant information. Lateralized alpha activity can be regarded as a marker of the task-specific adaptation of cortical excitability. Furthermore, memory-load dependent modulations in lateralized alpha oscillations were shown to relate to WM performance (Sauseng et al., 2009).

In children and older adults, we observed a reliable increase in lateralized posterior alpha power from low to medium load conditions, suggesting that both age groups engage the same neural mechanism as young adults. However, under high task-load conditions, hemispheric alpha power differences no longer exist in children and older adults, indicating that their task-specific adaptation of cortical excitability is less robust in situations in which WM capacity is overtaxed (see Fig. 2c). Thus, the efficiency of inhibitory control processes in children and older adults seem to be constrained by the amount of presented (irrelevant) information.

Taken together, the three studies suggest that children have not yet reached the younger adults' level of WM performance by middle childhood because the strategic component of WM, in particular, has not yet fully matured (cf. Bunge et al., 2002). At the same time, children perform better than older adults when presentation times are short, suggesting that their associative binding mechanisms are fairly well established (Cowan et al., 2006; Sander et al., 2011a,b). In line with neuroimaging studies showing that PFC regions are recruited during WM performance (e.g., Scherf et al., 2006; Wendelken et al., 2011) and cognitive control (Bunge et al., 2002), our results point to the continued development of top-down enhancement and inhibitory control processes (Dempster, 1992; Diamond, 2002) that contribute to WM performance. At the same time, our findings also show that the cognitive and neural mechanisms of top-down control are already in place by middle childhood, and that they can be put to work if the tasks at hand are structured appropriately within the functional range of the individual.

4. Potential implications for educational settings

Several implications for formal and informal educational settings can be derived from the results reviewed in this paper. In line with others, we would like to caution that findings obtained in the developmental neuroscience laboratory do not transfer directly to educational settings. There is an ongoing debate on how particular findings from neuroscience can be used to inform education (e.g. Ansari and Coch, 2006; Blakemore and Frith, 2005; Fischer et al., 2010; Goswami, 2006; Hille, 2011; Stern et al., 2005). We assume that insights from developmental neuroscience need to be rendered useful to derive informed decisions within the constraints and affordances of specific educational institutions or other instructional settings (see De Smedt et al., 2010). In this sense, education can be seen as a "technology" (Bunge, 1985) that integrates evidence from psychology, neuroscience, sociology, and the content knowledge of the various subject matters into social practices that foster learning and the cumulative build-up of knowledge among students.

Another caveat beyond this general issue relates to more specific methodological boundaries of our studies such as small sample sizes and sample selectivity that may also limit the generalizability to the classroom and other instructional scenarios (Ansari and Coch, 2006; Stern et al., 2005). For instance, the studies summarized above were all based on positively selected samples, as the children and teenagers had been recommended for, or were already attending, the school type with the highest entry requirements after elementary school in Germany (i.e., the Gymnasium). This selection bias was purposefully introduced to enhance the validity of comparisons to the groups of younger and older adults, which were also positively selected as well, admittedly at the cost of reducing generalizability to the general population.

Within the boundaries of this restricted generalizability, we identified commonalities and differences with regard to (episodic and working) memory development across the lifespan on behavioral and neural levels of analysis. Overall, the results support the notion that behaviorally similar performance outcomes may be brought about by relying on rather dissimilar sets of cognitive and neural mechanisms (Baltes et al., 2006; Craik and Bialystok, 2006). In particular, the various age groups seem to differentially rely on associative and strategic memory components when encoding to-be-learned contents. Accordingly, it seems appropriate that the age groups should be differentially supported during learning, for instance, in terms of strategy instruction or training on the one hand, and in terms of learner pacing and external memory offloading on the other hand.

Specifically, it appears advisable to structure formal and informal educational settings such that the educational environment is aligned to the needs and prerequisites of groups of learners differing in age. This recommendation is well in line with the literature on *aptitude–treatment interactions* (Cronbach and Snow, 1977) advocating that optimal learning occurs when an instructional design is matched to learners' particular prerequisites. Adaptively structured learning environments may be required in order to accommodate the age-graded differences in memory components recruited for learning. In the remainder of this article, we will elaborate the implications of this view in greater detail.

Presented in a nutshell, both the research on working and on episodic memory development reviewed here support the claim that memory performance of children relies predominantly on the associative component of memory, at least up to elementary school, and unless the use of strategies is explicitly instructed and supported. Apparently, the ease with which children integrate the various features of an episode into a compound memory trace forms the core of memory development. The strategic component of memory builds onto and follows the lead of the associative component with a certain time lag that is likely to vary from child to child and from task to task. The relation between the protracted maturation of the PFC and cognitive development has inspired influential theories of child development (Dempster, 1992; Diamond, 2002) and has been subsequently substantiated with more direct and cumulative evidence from behavioral neuroscience research. For example, increased WM performance in children has been shown to relate to functional changes in frontal and parietal cortex (Bunge and Wright, 2007; Klingberg, 2006; Nelson et al., 2000; Ofen et al., 2007; Olesen et al., 2007). In addition to these more localized changes, age-related differences in top-down control are associated with a strengthening of effective connectivity between frontal and posterior brain regions (Hwang et al., 2010). In line with this evidence, the studies from our group support the proposition that relatively low levels of strategic functioning in children reflect the relative immaturity of PFC, including its connections to more posterior brain areas. There is evidence that increased functional interactions between the mediotemporal lobe (MTL) and the PFC underlie the development of more effective memory encoding strategies in children and adolescents (Menon et al., 2005). In a similar vein, a recent study by Cho et al. (2011) showed differences in the activation pattern of MTL, PFC, and posterior parietal cortex between children using different strategies when working on mathematical problems. Longitudinal training studies in combination with neuroimaging techniques will be needed to further investigate how strategy instruction and training influence activation patterns and promote interactions between frontal and posterior brain regions.

The strategic components of memory performance addressed in our experiments are, on the one hand, related to learners' ability to engage in an active organization and integration of to be learned materials during encoding (e.g., using the Method of Loci or an imagery based strategy for learning word pairs). On the other hand, these components also relate to the ability to control the selection of relevant information for processing, while at the same time avoiding distractions due to the processing of irrelevant information – particularly in the context of high time pressure and high working memory load.

From an educational perspective, the strategic component bears some resemblance to pivotal concepts in current cognitive theories of instruction, such as Cognitive Load Theory (CLT; Sweller et al., 1998) and Cognitive Theory of Multimedia Learning (CTML; Mayer, 2005). These theories address how learning outcomes can be optimized by tailoring instructional designs and learning scenarios to the learner's memory limitations and other individual prerequisites of the learner (cf. Gerjets et al., 2009). Specifically, they focus on how instructional designs might be optimized in a way that they enable learners to: (a) focus on the selection of relevant materials; (b) avoid distractions due to processing of irrelevant information; and (c) engage in active strategies to organize and integrate the to-be-learned materials. Based on a rather global understanding of the constraints of human cognitive architecture and the resulting resource limitations, these theories have derived several instructional principles that are intended to tailor learning materials to working memory limitations. Typical examples include the use of multimodality and redundancy in instructional materials and to the efficient combination of charts and text.

Interestingly, developmental considerations are almost entirely absent from instructional theories such as CLT or CTML. Differential effects of instructional design as a function of the learner's age have not often been examined because most of the studies have been carried out with younger adults. For instance, an awareness of the possible implications of a decline of memory functioning in older adults for instructional design has only recently emerged within this field (e.g., Paas et al., 2005). From our perspective, introducing findings from developmental neuroscience like the ones summarized in this paper into cognitive theories of instruction bears the potential to arrive at age-graded instructional design recommendations. This observation applies both to older adults and children. In the case of children, building this link may inform instructional design decisions in school settings.

For instance, we found that younger children need to train strategies for the organization and integration of to-be-learned materials extensively because their strategic abilities are limited. This finding has direct implications for the design of instructional materials. Moreover, we also observed that older adults have major difficulties in overcoming the limitations of their associative abilities through extensive training. This suggests the use of instructional technologies that constantly cue the operation of the associative component by means of prompts, learner assessments, and feedback.

Many of the educational recommendations made by theories such as CLT and CTML are intended to help learners focus on relevant information and avoid the processing of irrelevant information (e.g., using cueing, providing temporal and spatial contiguity, avoiding seductive details or redundancy, cf. Mayer, 2005). The findings reported in this paper suggest that these considerations are especially relevant for children and older adults, even though most of the relevant studies in instructional design so far have been conducted with young adults. If appropriate environmental support was given to attenuate the adverse effects of less efficient strategic skills on task performance, children should be able to exploit their latent potential for associative processing. These considerations suggest that general instructional guidelines derived from theories of instructional design should be of particular relevance for children and older adults.

A further observation based on the data summarized in this article is that interindividual differences tend to be larger in children and older adults than among younger adults. The results of Brehmer et al. (2007) are particularly impressive in this regard. The authors found that the presentation time needed to reach a given level of performance varied by a factor of 7 in a relatively homogeneous group of 8–9-year-old children. To a considerable extent, this palpable heterogeneity is likely to reflect interindividual differences in the pace of cortical development (e.g., Shaw et al., 2006), rather than individual differences in ability that are stable over time (see also Humphreys and Davey, 1988). This implies that the proposed aptitude–treatment interaction perspective advocated with regard to age groups should also be applied to individuals within age groups. Instructional design recommendations that are based on available memory resources might have to be applied in a flexible way, depending on individual learner characteristics. As these recommendations concern, among other things, issues such as pacing, time for training, support for the selection of relevant and the avoidance of irrelevant information, one possible approach would be to use individualized instructional technology to allow teaching formats that permit learners to acquire knowledge in line with their developmental prerequisites and potential for improvement.

At the other end of the lifespan, older adults do not only suffer from a decline in strategic processes but also from pronounced difficulties in associative binding operations (Naveh-Benjamin, 2000; Shing et al., 2008), and may have problems in appropriately judging and using the novelty of presented information to form long lasting memories (e.g., Shing et al., 2009; Wilson et al., 2006). Nevertheless, older adults in general could recruit intact semantic knowledge capabilities (Baltes et al., 2006). Accordingly, educational settings for lifelong learning should concentrate on providing integrated materials that allow older adults to establish connections with their available semantic knowledge and that stimulate elaborations without relying on learner-initiated strategic processing (cf. Craik, 1983). Furthermore, older learners may particularly profit from highly structured environments that free cognitive resources to focus on novel aspects of presented information (Lindenberger and Lövden, 2006; Lindenberger et al., 2008).

In addition to the plea for age-related instructional design and for individualized instruction, particularly for children, a final recommendation refers to the age-comparative longitudinal follow-up data by Brehmer et al. (2008). In contrast to the adult groups, the children in this study showed spontaneous improvements in mnemonic skill when probed 11 months after the termination of training, presumably pointing to a powerful interaction of learning and maturation. This finding shows that the effects of strategy training can be relatively long-lasting, and may even increase over time, presumably in interaction with maturational processes. This finding implies that forms of training that address strategies for the handling of learning materials might be particularly efficient at younger ages due to their potential long-term effects – even if training needs to be more extensive for this age group.

5. Conclusion and outlook

Various forms of memory provide the basis for the acquisition of new skills and knowledge. Hence, developmental research on the modifiability of memory performance has important implications for education. According to the framework presented in this article, memory development consists of age-graded changes in strategic and associative components. From this perspective, educational settings should be tailored to the development of these two components in ways that are adapted to the individual learner. In the domain of episodic memory, providing individualized instructions and training for the handling of learning materials appears to be particularly promising. For instance, in the Shing et al. (2008) study, children learned to correctly recognize a very large number of German–Malay word pairs, suggesting that the mnemonic strategy used in this study can be profitably put to use when learning the vocabulary of a foreign language (cf. Bower, 1970). In the domain of working memory, providing information at the right pace and without too much distraction is critical. Existing instructional design theories that focus on the role of memory limitations can be used to integrate these findings into a broader educational perspective.

Developmental behavioral neuroscience aims at uncovering the neural mechanisms of developmental changes in behavior (e.g., Bunge, 2008; Dumontheil et al., 2010). This journey has just begun, and many exciting discoveries remain to be made. At present, very little is known about the extent to which teaching formats interact with the pace and outcome of cognitive development. Combining the insights from developmental behavioral neuroscience with research on instructional design may help to improve learning environments in ways that better reflect age-graded changes and individual differences in components of learning and memory.

Conflict of interest

There is no conflict of interest.

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