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What Connections Can We Draw Between Research on Long-Term Memory and Student Learning?

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INTRODUCTION TO THE SPECIAL ISSUE

Who we are and how we interact with the world around us hinges on long-term memory, the ability to remember past events and experiences. The ability to remember the past improves rapidly in the first years of life (e.g., Schneider & Pressley, 1997). As we grow up, we increasingly remember more details about when or where something happened, and become more sophisticated at using different strategies to facilitate learning and remembering (e.g., Schneider & Pressley, 1997). Many memories are created in school: we can often clearly picture encounters with our teachers and classmates or school field trips that we went to. At the same time, memory is critical for success in school, supporting language comprehension (e.g., Kutas & Federmeier, 2000) and reading (e.g., Blankenship, O'Neill, Ross, & Bell, 2015; Mirandola, Del Prete, Ghetti, & Cornoldi, 2011) as well as arithmetics (e.g., Blankenship et al., 2015; Qin et al., 2014).

Despite the centrality of memory for academic attainment, there have been few attempts to specify the key mechanisms by which children harness their developing memory systems to learn in school. There is a rich body of literature in psychology and neuroscience on the mechanisms that underlie various forms of memory and their development, but there have been few attempts to draw links between this well controlled, mechanistically detailed research and the richer, more complex world of classroom instruction. Indeed, it is difficult to directly apply this basic research to the classroom (e.g., Ofen, Yu, & Chen, 2016). By comparison, laboratory-based research on executive functions and motivation has provided important insights that are shaping educational practices (e.g., Blair, 2016; Diamond & Lee, 2011; Raghubar, Barnes, & Hecht, 2010). Here, we attempt to redress this imbalance by highlighting the work of researchers who study memory with a view to informing educational practices.

Many fascinating questions in this arena are ripe for exploration. What do educators, parents, and children need to know about different forms of memory, and when and how they develop? How do different memory systems interact during learning? How do children build on—or override—their prior knowledge? Why is active learning so beneficial? What role does future thinking play in a student's self-concept and motivation? Why do some children struggle to remember what they have learned, and what can be done to improve their mnemonic abilities? Does physical activity promote academic achievement, and if so, how?

This special issue includes empirical and review articles that begin to address these and other questions. The articles provide an overview of the ongoing research on learning and memory in childhood and beyond, and outline potential connections among laboratory-based research on memory functioning, development, and educational practice. Figure 1 outlines the connections among key themes explored in these articles.

A taxonomy of memory will be helpful for readers who are new to this area (see Squire, 2004 for a more detailed overview). Long-term memory, a term used to refer to memory traces that last for days, months, or years, is comprised of different systems associated with distinct biological substrates. Forms of long-term memory include habits and procedural skills such as riding a bicycle or playing the piano,

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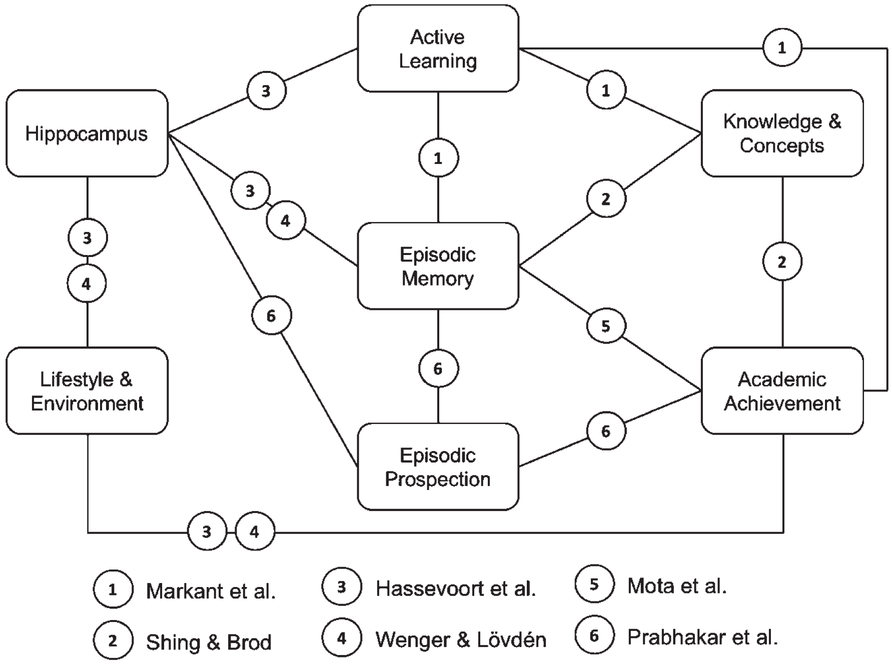

Fig. 1. Summary of the studies featured in the special issue titled *Memory Research: Implications for Education*. Boxes indicate topics covered across articles and numbers on the connecting lines refer to the specific article listed in the legend.

as well as memory for facts or events. Although all forms of memory are important for everyday functioning, we focus here on the types of long-term memory that are most directly relevant for learning in the classroom.

Episodic memory refers to memory for events that are rich in details about when or where they occurred in the past (Tulving, 1983). It depends on the ability to bind the different aspects of an event into a coherent memory episode. Autobiographical memories represent a special kind of episodic memory that involves personal experiences, feelings, and thoughts (e.g., Conway & Pleydell-Pearce, 2000). In contrast, semantic memory refers to facts and concepts about the world that are largely independent of the particular context in which they were acquired (Tulving, 1983). Thus, remembering seeing a lion in the zoo during a family visit last Christmas is an example of an episodic memory, whereas knowing that male lions have manes—without necessarily remembering when or where one learned this—is an example of a semantic memory. On the neural level, episodic and semantic memories are supported by neuroanatomically dissociable regions, including the temporal lobes and the prefrontal cortex (e.g., Squire, 2004). Episodic memory relies heavily on the hippocampus, whereas semantic memory depends on distributed cortical representations (e.g., Winocur, Moscovitch, & Bontempi, 2010).

During the school years, children get better at binding and recollecting the specific details of past episodes (e.g., Fandakova, Shing, & Lindenberger, 2013; Ghetti & Angelini, 2008), and develop more sophisticated concepts and knowledge structures (e.g., Bjorklund, 1987). These improvements are linked to developmental changes in the abovementioned neural systems (e.g., Ghetti & Bunge, 2012; Ofen & Shing, 2013). Additionally, children improve at focusing on and organizing to-be-remembered information (e.g., Fandakova, Lindenberger, & Shing, 2015; Wendelken, Baym, Rubens, Gazzaley, & Bunge, 2011). Indeed, students are not merely exposed to incoming information from the surrounding world, but can and must actively select what information to attend to, commit to memory, and retrieve at a later time point.

But how do we actively select what to learn? In the first article of the special issue, Markant, Ruggeri, Gureckis, and Xu review laboratory-based research demonstrating that providing students with the opportunity to actively control what and how to learn can enhance their event memory and facilitate the acquisition of new concepts. Markant and colleagues discuss several mechanisms that may underlie memory enhancements under active control, including the opportunity to adaptively select what to study next and when to do so, as well as the opportunity to create richer memory representations that incorporate additional event features. For example, memory of *performing* a physics experiment might include information about the objects used and the way in which the student interacted with them, whereas memory of *observing* an experiment would not include these sensory and motor components associated with the experience of active learning. The authors emphasize that benefits from the active control of learning are present early in childhood and may continue to increase with age as the underlying mechanisms develop further. Accordingly, different classroom activities that encourage active exploration and student-initiated control may have distinct effects depending on the mechanisms that they tap on as well as on the student's capacity to actively engage these mechanisms.

When we learn new information, semantic and episodic memory systems operate in parallel and closely interact. For example, we can acquire new semantic knowledge by extracting regularities occurring across multiple episodes (e.g., seeing a lion with a mane every time when we visit the zoo), and existing knowledge can in turn scaffold the integration and interpretation of new events (Preston & Eichenbaum, 2013). In the second article of this issue, Shing and Brod explore the different ways in which existing knowledge can influence the formation, storage, and retrieval of episodic memories. As the authors point out, the interactions between semantic and episodic memory systems are particularly pertinent during development, when children can increasingly rely on their growing knowledge base to facilitate encoding and retrieval of new memories. Shing and Brod review recent neuroimaging findings indicating that two distinct brain systems support the learning and retrieval of information, depending on whether it is consistent or inconsistent with existing knowledge. Protracted development of these brain systems may contribute to differences in students' ability to assess and effectively utilize existing knowledge at different ages. In future, this line of research could inform curriculum development by determining for which grade levels or subjects it could be particularly beneficial to highlight links between material learned across different classes and from year to year.

Shing and Brod also highlight the significant role of sleep and consolidation processes for semantic memory development. With accumulating evidence that most adolescents do not get sufficient sleep on school nights (e.g., Eaton et al., 2010), in part due to early school start times (e.g., Carskadon, Wolfson, Acebo, Tzischinsky, & Seifer, 1998), the reviewed work suggests that delaying school start times may have particularly beneficial effects on memory formation and the acquisition of new semantic knowledge.

As discussed above, the hippocampus is particularly important for long-term memory. It supports the binding of relational information such as when or where an event occurred and facilitates the flexible retrieval of different episodes (e.g., Eichenbaum, Yonelinas, & Ranganath, 2007). Thus, the hippocampus may be involved in supporting perception, cognition, and behavior beyond its involvement in memory (e.g., Rubin, Watson, Duff, & Cohen, 2014). Two articles in this special issue review recent findings about the hippocampus that have relevance for educational practices.

Hassevoort, Khan, Hillman, and Cohen review literature demonstrating that the hippocampus is particularly sensitive to environmental influences and experience, two aspects that are especially pertinent in the school context. Hassevoort and colleagues point to lifestyle factors that contribute to memory and academic performance, at least in part through their effects on hippocampal structure and function. The authors review evidence that aerobic fitness and diet affect hippocampal volume and predict individual differences in episodic memory. Over the course of development, the hippocampus undergoes changes both in terms of structural volume and engagement in learning and memory (e.g., Ghetti & Bunge, 2012), such that the effects of diverse health factors may be magnified during this developmental period. Thus, the authors suggest that emphasizing aerobic fitness and nutrition may be particularly effective in childhood, when hippocampal structure and function are still developing. This research is especially relevant in the context of schooling in the United States, considering the continuing cuts in gym classes (e.g., Baker, 2012) and low levels of physical activity among children and adolescents (e.g., Carlson et al., 2015). This work further suggests that changes in school meals to reduce saturated fatty acids and added sugars may not only help prevent obesity, but also positively affect learning and memory ability.

Wenger and Lövdén also underscore the point that the hippocampus may be more plastic during childhood than later in life. They argue that malleability of hippocampal structure and processing efficiency results from a mismatch between an individual's available resources and environmental demands. While experience-dependent changes in the hippocampus are important for learning (e.g., Maguire et al., 2000), the authors point out that they also confer vulnerability to negative influences, such as exposure to stress, which may be particularly disadvantageous in early childhood. Accordingly, Wenger and Lövdén suggest that students would gain most from educational practices and interventions that challenge them at the level of their individual capacity. Moreover, the authors note that education may in turn have long-lasting effects on the ability to learn new information and on hippocampal plasticity later in life. More studies are needed to examine the effects of being in school on memory development and the plasticity of the hippocampus. One promising way to tackle this question is by using school cutoff designs which compare children who are similar in age, but differ in their school experience by a year (Morrison, Smith, & Dow-Ehrensberger, 1995).

As noted previously, a barrier to the application of findings from the laboratory to educational contexts is the fact that these findings are frequently based on tightly controlled measures and manipulations of memory that bear little similarity to the school environment. The article by Mota and colleagues takes a step towards bringing those fields closer by investigating the relation between children's academic achievement and the way they spontaneously recount their memories. In a novel application of graph theory, the authors demonstrate that 6–8-year-olds with superior reading ability and higher IQ test scores were more likely to report their memories with a larger number of different words and more—and more diverse—connections among them. Further, the complexity of children's memory reports predicted future reading ability, measured both concurrently and 3–4 months later, over and above the effects of IQ. As such, analyzing the complexity of children's naturalistic speech provides insights into memory organization, and could be helpful for identifying children who may need additional scaffolding in learning to read. This novel paradigm provides fodder for future research on the relationships between various types of memory reports and different aspects of cognitive functioning and academic performance.

Thus far, we have discussed how the ability to remember the past contributes to scholastic achievement. However, Prabhakar, Coughlin, and Ghetti argue that the ability to envision the future may also be important. Neuroimaging research has revealed that multiple brain regions involved in remembering the past are also engaged when we imagine the future, thereby enabling us to plan for the future and to anticipate possible outcomes of our actions (Schacter, Addis, & Buckner, 2007). How does episodic prospection, the ability to form a mental representation of a personal future event, develop? And in what ways does it affect children and adolescents' priorities and behavior? Prabhakar and colleagues examine these questions, emphasizing that memory ability and the hippocampus play a critical role in retrieving and recombining details from past experiences to form a mental representation of a future event. The authors note that individuals' self-concept may also contribute to episodic prospection by guiding which past events are included in imagining the future. The development of self-concept during childhood and adolescence may therefore, together with memory improvements, contribute to the prolonged development of the ability to envision oneself in the future. Prabhakar and colleagues suggest that episodic prospection may be particularly beneficial during the school years. For example, students with more developed episodic prospection may engage in academic behaviors that they believe are likely to promote the future selves they envision, such as completing homework and studying for exams. This final contribution of the special issue highlights the adaptive nature of long-term memory and the multiple ways in which it is essential not only for how we act in the present, but also for how we plan and prepare for the future.

Together, the articles in this special issue provide an overview of the current state of laboratory-based research on long-term memory, its development, and underlying neurocognitive mechanisms. Even though each of the articles is focused on a specific aspect of memory, the different topics are closely connected (see Figure 1). Several current trends and areas for future investigation emerge from the work presented here.

THE POTENTIAL OF LABORATORY-BASED RESEARCH TO INFORM ACADEMIC INSTRUCTION

The articles in this special issue showcase the constructive ways in which different levels of observation, such as behavioral performance and measures of brain structure and function, can be combined into laboratory-based research to elucidate the key factors contributing to learning and memory ability. A common theme across the articles is that insights from memory research can inform educational practices in several different ways. First, this works suggests that teachers can facilitate children's learning and memory, for example by creating opportunities for active learning or drawing on prior knowledge. Second, the articles outline ways in which educators may optimize interventions aiming to improve learning and school success, for example by using episodic prospection exercises and challenging different students at their individual capacity. Finally, the work highlighting the strong link between brain health and bodily health provides a rationale for adjusting school start times, including physical education in the school day, improving cafeteria food, and—furthermore—teaching students about the importance of good sleep, exercise, and diet.

The basic neural and cognitive mechanisms of learning and memory exhibit distinct developmental trajectories, such that different educational practices may be more or less effective or impactful depending on students' age. However, the behaviors of interest to educators are complex, arising from interactions among multiple underlying mechanisms. Collaborations among psychologists, neuroscientists, educational researchers, and educators are needed to bring research questions and methods closer to the reality of the classroom, in order to directly elucidate the roles of episodic and semantic memory in educational practice.

INDIVIDUAL DIFFERENCES AND ATYPICAL MEMORY DEVELOPMENT

Although comparisons of learning and memory capacity among age groups provide insights into the general mechanisms governing memory functioning at different points of the lifespan, there exists at any given age considerable variation in these abilities. Several of the contributions to this special issue describe how such variability among individuals results from a unique combination of experience and environmental factors that together shape the neurocognitive mechanisms supporting learning and memory. This heterogeneity is especially pronounced in childhood—a fact that should be considered in the development and implementation of school curricula and interventions, particularly in light of the different challenges that children face across neighborhoods and school districts. Here, a targeted approach to designing instruction that takes into account school demographics may be particularly promising for helping children learn more effectively.

Beyond the individual differences in memory that exist among typically developing children, we must also consider extreme cases; indeed, memory deficits are observed in a number of neuropsychiatric and neurodevelopmental disorders. Episodic memory deficits have been reported in association with depression (e.g., Burt, Zembar, & Niederehe, 1995) and schizophrenia (e.g., Aleman, Hijman, de Haan, & Kahn, 1999), and are frequently observed in autism spectrum disorder (e.g., Boucher, Mayes, & Bigham, 2012) and fragile X syndrome (e.g., Ornstein et al., 2008). Acquired brain injury can also affect memory, ranging from profound deficits in cases of developmental amnesia (e.g., Vargha-Khadem et al., 1997) to milder conditions such as cerebral hypoxia or type I diabetes (e.g., Ghetti, Lee, Sims, Demaster, & Glaser, 2009). At present, little is known about the extent to which these various conditions impact academic achievement. Understanding how each of the memory systems is affected in specific pediatric populations could eventually inform interventions and instructional practices so as to ameliorate memory deficits, or at the very least help children to compensate for them by relying on intact neurocognitive systems.

HOW DOES EDUCATION AFFECT BRAIN AND MEMORY DEVELOPMENT?

Just as neurocognitive development affects school achievement, so too might the experience of schooling affect neurocognitive development. In particular, schooling may exert a profound influence on memory development (cf. McCandliss, 2010). Children acquire a vast amount of knowledge in the classroom; this is where they also become more proficient in strategically structuring their learning and remembering. It is, however, not easy to measure how educational experience affects the developing mind and brain; thus, there are many open questions. For example, how do memory performance and the underlying brain networks vary with exposure to different types of instruction? How does the increased demand to remember and acquire new conceptual knowledge in school affect brain development, in particularly the regions crucial for episodic and semantic memory? Finally, as the structural connections between the hippocampus and prefrontal brain areas supporting executive functioning are strengthened with development (e.g., Lebel & Beaulieu, 2011), how does the use of novel elaborative learning strategies in school affect hippocampal development and change? One promising way to probe these questions is by comparing children of the same age who are at different points in their education. Another is to compare curricular approaches between classrooms within a single school. A third approach that touches on broader issues but is fraught with challenges is the comparison of children from different types of schools, or—at the extreme—different educational systems.

Finally, in addition to examining the bidirectional relationships between memory and formal education, we must bear in mind that a considerable part of students' learning happens outside of school, while interacting with family and peers, engaging in extracurricular activities, or completing homework. Future research that investigates how these learning contexts shape memory at different ages may help structure learning opportunities accordingly. For example, parents' strategic behavior may play a key role in children's development of memory strategies in early childhood (e.g., Gueler, Larkina, Kleinknecht, & Bauer, 2010), whereas peer interactions may have a bigger impact during adolescence (e.g., Blakemore & Robbins, 2012; Galván, 2014).

CONCLUSION

Our goal in producing this special issue has been to highlight current psychological and neuroscientific research on memory that is relevant for education. However, to make substantive progress in this endeavor, we need a multi-way conversation among laboratory-based researchers, school-based researchers, and educators. Tasks used to study memory in the laboratory are often far removed from the mnemonic challenges that students face when learning new material or studying for exams. As such, input from educators is needed—not only to increase the real-world significance of this research, but also to provide insights into how people learn complex material in a complex environment.

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