MIND, BRAIN, AND EDUCATION

Enhanced Memory as a Common Effect of Active Learning

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ABSTRACT— Despite widespread consensus among educators that *active learning* leads to better outcomes than comparatively passive forms of instruction, it is often unclear why these benefits arise. In this article, we review research showing that the opportunity to control the information experienced while learning leads to improved memory relative to situations where control is absent. By integrating findings from a wide range of experimental paradigms, we identify a set of distinct mechanisms that mediate these effects, including the formation of distinctive sensorimotor associations, elaborative encoding due to goal-directed exploration, improved co-ordination of selective attention and encoding, adaptive selection of material based on existing memory, and metacognitive monitoring. Examining these mechanisms provides new insights into the effects of active learning, including how different forms of active control lead to improved outcomes relative to more traditional, passive instruction.

One of the most widespread ideas in education is the virtue of being an *active* learner. Over more than half a century, a succession of educational theories have each advanced a new image of what it means to be active during learning and the purported benefits relative to passive instructional conditions. These theories—including discovery learning (Bruner, 1961), inquiry learning (Kuhn, Black, Keselman, & Kaplan, 2000), experiential learning (Kolb, 1984), constructivism (Steffe & Gale, 1995), and self-regulated learning (Boekaerts, 1997)—vary in their breadth and emphasis but share the view that active learning leads to improved outcomes, a claim that is often supported in comparisons with more traditional forms of passive, lecture-based teaching (Bonwell & Eison, 1991; Freeman et al., 2014).

Despite the prominence of this idea, it is often unclear *why* active learning succeeds or fails in real-world settings, because active instruction typically varies in multiple ways from passive learning. Indeed, the concept of active learning has grown to encompass a huge variety of instructional techniques, usually referring to some combination of increased physical activity or interaction, deeper processing, elaboration or explanation of material, planning of learning activities, question asking, metacognitive monitoring, and social collaboration. As a result of this diversity, it is difficult to identify the causal factors that lead to performance differences under active learning or to predict whether such effects will generalize to other kinds of activities or materials. This difficulty is underscored by ongoing debates over the merits of active learning relative to guided instruction (Kirschner, Sweller, & Clark, 2006; Mayer, 2004; Prince, 2004) and attempts to create precise taxonomies of active behaviors and their predicted effects on learning (Chi, 2009).

One approach for understanding the effects of active instruction is to identify how it engages underlying cognitive processes related to learning and memory (Gureckis & Markant, 2012). In this article, we focus on a principle shared by nearly all definitions of active learning: that students should have the opportunity to exert control over the learning experience, including the selection, sequencing, or pacing of new information. We review a broad range of experimental evidence showing that such active control can lead to improvements in various forms of memory (including episodic memory) relative to passive conditions that lack the same opportunity for control, suggesting that enhanced memory may be a common outcome of active learning. Moreover, we show that these enhancements can arise from

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a number of distinct mechanisms, depending on the kinds of control afforded by an instructional activity.

We begin by surveying experimental research that has examined the impact of active control on episodic memory. Comparing the types of tasks and materials used in existing work serves to highlight a set of mechanisms[1] through which active control influences memory, and which are diminished or absent during passive, observational experience. A critical contribution of this experimental work is the ability to separate the effects of exercising control from its consequences in terms of the information experienced during learning. For instance, students who ask questions during class may benefit for two reasons: they receive answers that are useful (i.e., a change in information), and they make decisions about which questions to ask (i.e., a process involved in exerting control). To account for this confound, many of the reviewed studies employ *yoked* experimental designs involving pairs of learners, wherein an active participant controls the flow of information during learning, while a second, yoked participant observes the experience generated by the active participant. This experimental approach is highly simplified relative to real-world instructional settings like classrooms, where typical activities involve multiple levels of control on the part of the student, each with its own effects on the information that is experienced. However, it makes it possible to isolate the causal mechanisms underlying the effects of control on memory, providing insight into the outcomes of different forms of active instruction.

In the second part of the article, we consider the generalizability of these findings with respect to three issues of relevance to educators. First, we examine the potential role of enhanced memory in inquiry-based learning, a common form of active instruction that is often associated with improvements in measures of conceptual learning. Second, we review the extent to which the effects of active control on memory are present over the course of development. Finally, we discuss the implications of these findings for the way that educators manage the trade-off between learner control and guided instruction.

HOW DOES ACTIVE CONTROL AFFECT EPISODIC MEMORY? IDENTIFYING KEY MECHANISMS

Many educational philosophies advocate for independent, curiosity-driven exploration during learning. This vision is perhaps best exemplified by the Montessori practice, which emphasizes freedom of movement and manipulation of physical objects in a classroom, with exploration and play central to the design of learning activities (Montessori, 1912/1964; see also Gray, 2013). However, elements of active exploration are increasingly common in more structured educational contexts as well. For instance, experiential or problem-based learning formats often involve direct manipulation or exploration of simulated microworlds or multimedia interfaces (De Jong, Linn, & Zacharia, 2013; Rieber, 1996). Recent research on computer-based instruction has examined how learning outcomes depend on the level of interactivity in these settings (e.g., the ability to control the pacing or sequence of animations or recorded lectures) but has produced inconsistent findings (Scheiter & Gerjets, 2007), particularly with respect to memory retention (Evans & Gibbons, 2007; Yildirim, Ozden, & Aksu, 2001). As noted by Scheiter and Gerjets (2007), one limitation of this line of research is a failure to account for differences in information that arise from learner control, making it difficult to assess how the act of exploring itself affects performance.

Although the importance of active exploration to perceptual and cognitive development has long been recognized in psychology (E. J. Gibson, 1988; Held & Hein, 1963), its impact on memory in particular has become increasingly evident through the use of yoked experimental paradigms. For instance, a number of studies have shown that certain forms of spatial memory (e.g., memory for the distances between landmarks) are enhanced by active navigation of the environment (see Chrastil & Warren, 2012 for a review). In these experiments, an active participant is (sometimes literally) in the driver's seat, making decisions and/or physically controlling movement through a real or virtual environment, while a yoked partner passively observes the same experience. For example, participants who walk through a series of hallways typically have better memory for the experienced route as compared to yoked participants who are conveyed along the same path in a wheelchair (cf. Chrastil & Warren, 2012).

Even when limited to relatively simple interactions with a set of stimuli (rather than navigating a complex spatial environment), active control is typically associated with improved memory (Craddock, Martinovic, & Lawson, 2011; Harman, Keith Humphrey, & Goodale, 1999; Liu, Ward, & Markall, 2007; Luursema & Verwey, 2011; Meijer & Van der Lubbe, 2011; Trewartha, Case, & Flanagan, 2014; Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011), despite the fact that the presented stimuli are matched within active/yoked pairs of participants. As one example, Harman et al. (1999) found that actively manipulating objects on a display (i.e., rotating a novel three-dimensional shape during a study period) led to faster recognition during a subsequent test than viewing videos of the same interactions.

Given that active and yoked participants in these experiments share the same experience, why does active control lead to better memory for that experience relative to passive observation? In the remainder of this section, we review a set of mechanisms that may underlie this kind of enhancement, drawing on a range of research topics including spatial navigation, goal-directed search, and self-guided study. We focus our review on those findings that best illustrate a particular mechanism's effect on episodic memory. Note, however, that experimental tasks vary widely in the types of control involved in active conditions, and, as a result, some may engage more than one of the mechanisms described below.

Encoding of Distinctive Sensorimotor Associations

A basic function of episodic memory is to encode associations between different features of an experience, which then form the basis for later recollection. Retrieval of a specific element is more likely when it is involved in a rich network of associations than when it is encoded in isolation (Anderson & Bower, 1972; Craik & Tulving, 1975; Tulving & Thomson, 1973). For instance, it is easier to remember what we ate for breakfast yesterday when other features of the same event can be recalled, such as the morning news report that was playing in the background. Actions involved in exploration may play a similar role by generating additional cues that are bound to stimulus information (Hommel, 2004). According to this view, the physical act of exploring—moving to a new location, manipulating an object, searching for a toy in a bin, and the like—leads to a richer episodic representation that increases the likelihood of retrieving information about experienced stimuli from memory. As put by J. J. Gibson (1962), "to *apply* a stimulus to an observer is not the same as for an observer to *obtain* a stimulus" (p. 490). The act of *obtaining* is encoded in the memory for an event and provides additional cues that can facilitate later remembering.

A striking demonstration of this idea comes from a study by Trewartha et al. (2014) that examined memory for the spatial locations of objects arranged on a table. They compared active reaching (in which the participant moved his or her arm to touch a highlighted target object) to a passive condition in which a robot moved the participant's arm to the same location. When later asked to recall where targets had appeared, memory for their locations was better in the active condition, despite the fact that participants in both conditions experienced the same visual environment and limb movement (suggesting that the enhancement could not arise from proprioceptive information about their arm position, another potential source of associations). The authors argued that internal motor commands that active participants generated in order to execute reach movements contributed to a richer representation in memory, which subsequently increased the likelihood of recalling targets' locations.

Unlike exploration, in which the learner generates actions that are causally related to events that occur in the environment, passive observation is a *receptive* mode of experiencing stimuli that is externally driven and largely independent of the observer's actions (Markant & Gureckis, 2014; Murray & Gregg, 1969). In addition to taking fewer actions themselves, passive observers lack information that is generated in the course of physical exploration. Consider a child who, while playing with a new stuffed animal, discovers that squeezing the toy in a particular location causes it to squeak. Although a passive observer might easily infer the causal mechanism at work (e.g., *squeeze the head → squeak*), the observer will lack the sensorimotor association that constitutes part of the actor's memory for the same event (i.e., the squeezing action coinciding with the sound). This idea is consistent with a separate line of research showing that enacting a verbal instruction (e.g., *break the toothpick*) leads to more successful recall compared to hearing the instruction alone (Cohen, 1989) or observing another person carry it out (Engelkamp, Zimmer, Mohr, & Sellen, 1994; for a review, see Nilsson, 2000). In contrast to passive observation, active exploration generates a distinctive sensorimotor context in which events are encoded and which can then facilitate later retrieval (cf. Eysenck, 1979).

Elaborative Encoding Through Goal-Directed Search and Planning

Exploration typically implies an element of goal-directed search, wherein the active learner makes decisions about where to look or how to navigate a space. In the spatial learning domain, there is recent evidence that such decision making is sufficient to enhance learning of the environment, even in the absence of physical interaction or control of movement. Plancher, Barra, Orriols, and Piolino (2013) compared active drivers and yoked passengers in a virtual driving experiment. Active participants were assigned to one of two conditions: an *interaction* condition, in which they drove a car along a route dictated by the experimenter, and a *planning* condition, in which they decided which direction to turn at each intersection and their choices were carried out by the experimenter. Compared to passive observation, in which participants simply watched a video of the driving experience generated by participants in the interaction condition, both active conditions led to better memory for the layout of the virtual environment and the route taken. Moreover, performance in the planning condition was higher than in the interaction condition, suggesting that deciding how to explore enhanced memory independently of the physical act of exploring itself.

Interestingly, the same study found the opposite pattern in recognition memory for objects encountered along the route, with passive observers showing better recognition relative to both active conditions (see also Brooks, 1999). This result raises the possibility that the mnemonic benefits of active exploration are specific to functional information that is relevant to making exploratory decisions, whereas incidental memory for goal-irrelevant information

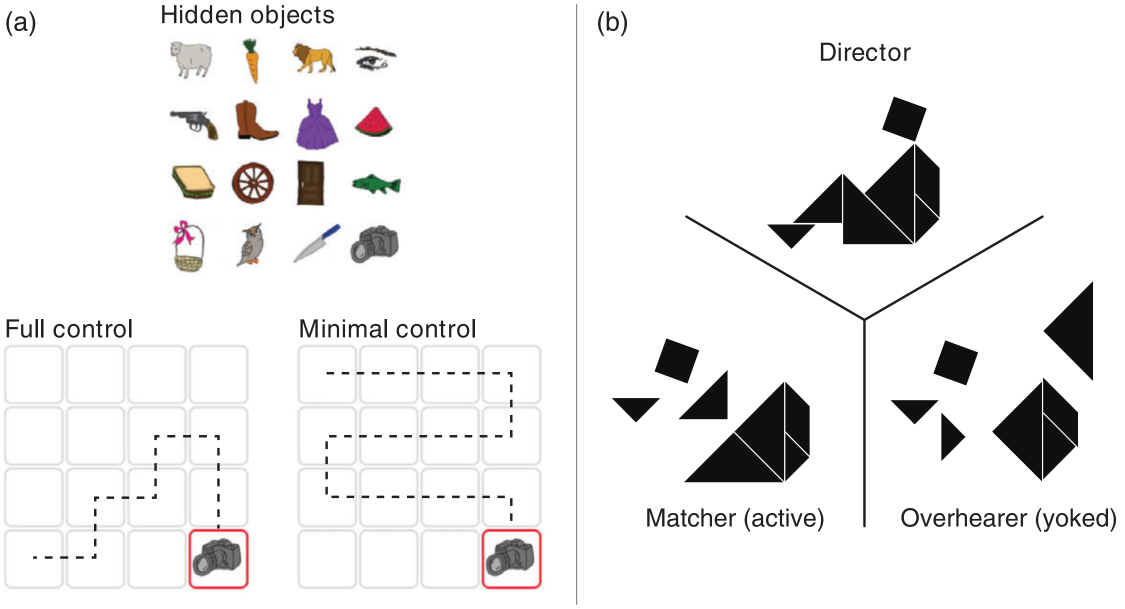

Fig. 1. (a) Depiction of object study task (Markant et al., 2014; Ruggeri, Markant, Gureckis, & Xu 2016) in which participants study iconic objects hidden in a grid. During active study with full control, participants decide where to move the window and how long to study each object. During active study with minimal control, participants only decide when to show the next item—the window follows a predetermined path, and objects are displayed for a fixed amount of time. (b) Illustration of the experimental task in Schober and Clark (1989). Three participants are seated in the same room, separated by dividers. The *director* gives instructions to the *matcher* as to how to arrange a set of shapes, while the yoked *overhearer* listens to their conversation and attempts to recreate the same arrangement.

could be impaired or unchanged relative to passive observation. According to this view, exploratory decision making is a constructivist process involving the formation of a mental representation of a space in order to support navigation decisions. Like other examples of elaborative encoding, in which stimuli are embedded in a distinctive, self-generated context (e.g., Bower, 1970), deciding how to search typically entails generating potential action plans and mentally simulating their effects based on features of the current state (e.g., one's location along a route relative to the goal location). This aspect of goal-directed search may support later retrieval (Voss, Galvan, & Gonsalves, 2011), an idea that is consistent with recent work implicating episodic memory in scene construction (Hassabis & Maguire, 2007) and information foraging (Johnson, Varberg, Benhardus, Maahs, & Schrater, 2012). Without a need to engage in exploratory decision making, passive observers are less likely to construct a representation of the search space and may instead allocate their attention to other aspects of the environment.

Co-ordination of Selective Attention and Memory Encoding

In many interactive environments, active control implies that learners can adjust the pacing of new information to match their own attentional state. In contrast, passive observers may experience momentary lapses in attention (e.g., because of mind wandering or continued processing of earlier information) coinciding with the presentation of new material. A recent study by Markant, DuBrow, Davachi, and Gureckis (2014) suggests that this attentional co-ordination is one reason why active control leads to improved memory for materials encountered during exploration. The authors employed a memory task involving objects that were spatially arranged in a series of grids, with only one object visible at any point in time through a moving window (Figure 1a; see also Voss, Gonsalves et al., 2011). Participants alternated between active control blocks, in which they could control the movement of the window, and yoked blocks, in which they observed the study sequence that a previous participant had actively generated. Different levels of active control led to similar advantages in recognition memory as compared to yoked observation, including when active participants could only control the timing of new study episodes (i.e., pressing a button to reveal a preselected item for a fixed duration).

Episodic encoding is known to depend on attentional control, because memory performance declines when attention is divided during encoding (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). However, retention improves when the amount of time spent encoding each item is self-paced rather than set by an experimenter (Craik, Naveh-Benjamin, Ishaik, & Anderson, 2000), suggesting that self-paced learners can adjust the timing of study episodes based on their attentional state. Similarly, active control may allow the learner to co-ordinate the presentation of new material with their attentional resources (e.g., by delaying new items until they are finished processing prior material), a process that is especially advantageous in environments where many stimuli compete for attention, but only task-relevant information must be selected for learning (Chun & Turk-Browne, 2007). Like the other mechanisms described above, this self-pacing involves low-level, moment-to-moment processes that support interaction with a learning environment. Taken together, these results suggest that activities in which the flow of information is independent of the learner's state (as is the case in passive observation) will tend to produce poorer episodic memory as compared to active control.

Adaptive Selection of Material

Although educators cite a number of reasons for placing control in the hands of students (e.g., increased motivation), one of the most common arguments is that such control is a means for adaptive, individualized instruction (Bonwell & Eison, 1991). Even the best lecture is likely to have an uneven impact in a class of students with diverse backgrounds and abilities. Active students have the opportunity to shape the learning experience to their specific needs. An important question is whether, given this opportunity, students make adaptive decisions about how to study based on their existing knowledge.

A large body of work has examined how metacognitive mechanisms—particularly the process of monitoring one's own memory—guide students' decisions about what material to focus on or how to structure a learning experience (for a review, see Finley, Tullis, & Benjamin, 2010). Active learners are able to focus on material that they do not understand or have difficulty remembering while avoiding spending time on material that is already mastered or recognized as too difficult to learn (Nelson, 1993; Nelson & Leonesio, 1988). This advantage is the focus of research on study time allocation, which typically involves sets of items that must be memorized and which vary in difficulty (e.g., in pre-existing familiarity or relatedness). For instance, a typical study might involve learning to associate objects or words, such as English–Spanish translations like *family—familia* or *cranberry—arandano*. In contrast to the studies described above, this area of research tends to rely on experimental paradigms that minimize physical interaction or exploration. Under active conditions, participants decide how to structure further study, including which items to spend time on and for how long, a problem that is similar to flashcard-based study techniques that are widely used across different stages of education.

According to the *region of proximal learning* theory (Metcalfe, 2009), learners should allocate study time by first evaluating items' existing strengths in memory and then studying those that are close to mastery. By allocating effort in this way, students can increase the number of items that are successfully encoded while avoiding items that are already known or that may be too difficult to commit to memory within the study period (i.e., items outside the region of proximal learning). A number of studies have shown that this active control of study leads to better memory performance than when study time is randomly allocated or dictated by another person (Kornell & Metcalfe, 2006; Metcalfe & Kornell, 2005; Tullis & Benjamin, 2011). These results highlight the shortcomings of "one-size-fits-all" study, even when designed to account for the difficulty of the materials. For example, Tullis and Benjamin (2011) compared three groups of participants: a *self-paced* group that controlled how long each item was studied, a *fixed* group that studied all items for the same amount of time, and a *normative* group that studied items for different amounts of time depending on their difficulty (as measured by the performance of an independent group of participants, with harder items allocated more study time). Surprisingly, the normative study condition was associated with the worst performance overall. The finding that the self-paced group performed better than both normative and fixed groups suggests that participants made adaptive study decisions in a way that reflected their existing memory. In other words, the choices made during self-guided study tend to be idiosyncratic: the experience generated by one student may be less effective for a yoked partner with different needs or existing memory (see also Markant et al., 2014).

Enhanced Memory Due to Metacognitive Monitoring

Beyond the benefits of individualizing study experiences, the metacognitive monitoring involved in making study decisions may itself facilitate memory, particularly when those decisions involve attempts to retrieve information from memory. For example, when deciding whether to study the definition of a term seen on the face of a flashcard, a student may first attempt to retrieve the definition from memory. This retrieval practice has been shown to improve subsequent memory for the association relative to mere re-presentation of the same item in the absence of retrieval attempts (Karpicke, 2009; Kimball & Metcalfe, 2003; Roediger & Karpicke, 2006). Like the facilitative effect of goal-directed search, making memory-based study decisions through retrieval practice can independently improve retention regardless of how those decisions are then carried out.

A further benefit of active control may therefore be that it naturally encourages students to engage in metacognitive monitoring that would not have occurred otherwise, including retrieval practice. It is important to note, however, that students use a wide range of strategies for making study decisions and are often unaware of how those strategies affect retention. For example, most students view retrieval practice as an assessment strategy (i.e., "how much have I learned?") rather than a way to strengthen memory (Kornell & Son, 2009; Roediger & Karpicke, 2006). Karpicke (2009) showed that this belief affects whether people engage in retrieval practice, such that people are less likely to test their memory than to simply restudy a pair (particularly at early stages of learning when they have low confidence in their ability to retrieve the target). More generally, students tend to be unaware of longer term study strategies that improve retention like spaced repetition (Kornell & Bjork, 2007), consistent with an overall lack of strategic knowledge about how to structure study. Thus, maximizing the benefits of active control may depend on training students in study strategies that improve memory (Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013) or designing active learning tasks that directly engage metacognitive decision making.

BROADER IMPLICATIONS

We have highlighted a number of ways in which active control affects episodic memory. Many of these lab-based studies involve variants of "active" behaviors common to educational settings, including physical interaction, self-pacing, metacognitive monitoring, and goal-driven exploration. Taken together, this work suggests that enhanced memory may be a common effect of these activities, but arises from different mechanisms depending on the kinds of control and goals involved. In the remainder of the article, we discuss the generalizability of these results with respect to three issues: (1) the effects of active control on inquiry-based, conceptual learning, (2) the developmental trajectory of active control and its impact on memory, and (3) the implications of these findings for determining the right balance between learner control and structured guidance in educational settings.

Inquiry and Conceptual Learning

Inquiry-based instruction is one of the most prominent examples of active learning in education, as evidenced by its central role in national curricular standards across a wide range of content areas (Saunders-Stewart, Gyles, & Shore, 2012). During active inquiry a student asks questions, collects information, or conducts experiments in a structured, hypothesis-driven manner. Although inquiry may involve elements of spatially grounded exploration or metacognitive control like those discussed above, it is distinguished by the need for students to go beyond the information present in the environment, to generate useful evidence in order to learn a new concept or test competing explanations of some phenomenon. Like self-guided study, it allows learners to adaptively gather information that is helpful given what they already know while avoiding information that is redundant or beyond their grasp.

A crucial, unresolved question is whether the process of active inquiry leads to enhanced episodic memory for the resulting experience. Existing classroom-based research offers little insight into this question. Studies of inquiry-based instruction have predominantly focused on outcomes related to conceptual knowledge, including comprehension, concept inventories, or summative assessments like final exams (cf. Freeman et al., 2014; Saunders-Stewart et al., 2012), in keeping with a general tendency by educational psychologists to focus on conceptual and procedural learning rather than episodic memory for the events experienced during instruction (Martin, 1993). This gap is particularly striking given that standards for inquiry-based instruction strongly emphasize grounding inquiry in direct experiences that are likely to rely heavily on episodic memory (e.g., conducting experiments to investigate meaningful questions and making sense of empirical evidence; Loucks-Horsley & Olson, 2000). At present, a similar gap persists in lab-based research, because controlled comparisons of active and yoked concept learning have typically not assessed memory for the training experience. The contribution of episodic memory to gains in conceptual knowledge from active inquiry therefore remains an open question, despite the fact that it is thought to play an important role in the formation of semantic memory (McClelland, McNaughton, & O'Reilly, 1995), concept acquisition (Pothos and Wills, 2011), and transfer through analogical reasoning (Vendetti, Matlen, Richland, & Bunge, 2015). In the following, we describe two examples of how active inquiry facilitates conceptual learning in the lab and consider how enhanced episodic memory may play a role in those improvements.

Direct comparisons of active inquiry and yoked observation have generally found that active learners are more successful at acquiring simple concepts (Markant & Gureckis, 2014). One early example by Hunt (1965) compared active and passive learning of an artificial grammar, a set of rules that defined whether "statements" (i.e., strings of letters such as ZLT) were grammatical. Active learners generated statements and received feedback about whether they were consistent with the grammar, while yoked participants learned from the same set of statements through observation. At the end of training, active learners made fewer errors when judging the grammaticality of novel statements, showing better acquisition of the underlying grammar. One explanation for this result focuses on the usefulness of the information generated by active learners, who were able to test hypotheses about the grammar as they learned. For instance, if an active learner thought that a Z must always be followed by a T, he or she could generate a counterexample (e.g., ZZZ) to test that belief, a direct hypothesis-testing process that is unavailable to a yoked partner. This kind of gap may arise whenever students have diverging beliefs or hypotheses but differ in their ability to control the selection of information (Markant & Gureckis, 2014).

Although studies of conceptual learning have predominantly focused on this informational benefit of active control, it is likely that typical inquiry-based activities engage many of the same memory-based mechanisms reviewed above. A study by Schober and Clark (1989) provides a compelling starting point for examining how differences in memory encoding might contribute to the gap between active and yoked learning. In this experiment (Figure 1b), an active participant (the *matcher*) conversed with a second participant (the *director*) to determine how to arrange a set of shapes on a table. A third, yoked participant (the *overhearer*) passively listened to the same conversation and attempted to recreate the target arrangement. Despite the seeming simplicity of the task, yoked listeners were at a distinct disadvantage relative to active matchers in their ability to reproduce the correct arrangement of objects. Beyond the opportunity to gather useful information, active matchers may have benefited in a number of ways from exercising control. Matchers could influence the pacing of new information and request repetitions or clarifications of instructions, allowing them to co-ordinate attention with the flow of information and correct any failures to process previous directions. Asking questions likely involved generating potential queries and predicting how the answers would help them achieve the goal, a planning process that was absent in the overhearing condition. Moreover, matchers contributed to a shared vocabulary to reference the materials, generating meaningful associations with individual objects in collaboration with the director. Even when directors gave effective instructions, yoked listeners were less able to follow them and appeared to lack the necessary contextual understanding to put them to use. Thus, although the opportunity to test hypotheses is a powerful learning aid, this example suggests that it cannot fully capture the effects of exercising control during active inquiry, including changes in the way that people construct and encode the experiences that form the basis for learning.

The same question can be applied to studies of causal learning, which often involve concepts that can only be acquired through active control (e.g., intervening on a causal system to distinguish correlation from causation). Recent research has examined how people make active interventions to generate evidence that distinguishes between possible causal explanations (Coenen, Rehder, & Gureckis, 2015; Gopnik et al., 2004; Lagnado & Sloman, 2004; Rottman & Keil, 2012; Sobel & Kushnir, 2006; Steyvers, Tenenbaum, Wagenmakers, & Blum, 2003). For example, Sobel and Kushnir (2006) created a task in which people learned about how a set of buttons led to the activation of a light. Participants either actively decided what test to conduct (pressing a combination of buttons) or were instructed to passively carry out the same test. Active participants were more likely to learn the correct causal structure despite the equivalence of the training experience, supporting the idea that the process of inquiry itself can facilitate learning independent of the information it generates. Although these studies tend to focus on the tests people generate during active causal learning, the mechanisms discussed in previous sections may also contribute to gains in learning relative to passive observation. For instance, because effects follow their causes in time, generating a causal intervention may aid in co-ordinating attention to the presentation of the effect (Lagnado & Sloman, 2004; see also McCormack, Frosch, Patrick, & Lagnado, 2015). Alternatively, deciding how to intervene on a system (i.e., designing an experiment) may lead learners to generate causal explanations, an elaborative process that has been shown to lead to improved retention (Dunlosky et al., 2013) but which may be less likely when interventions are simply observed.

Thus, lab-based studies of both conceptual and causal learning have largely focused on the informational benefit of active learning: the ability to generate evidence that is useful given one's own existing knowledge. Understanding the cognitive basis of inquiry-based instruction will require further research examining how active control interacts with episodic memory during such activities and assessing its impact relative to more passive forms of experience.

Effects of Active Control During Development

An important question for educators is how the effects of active control depend on a student's developmental stage. Although existing developmental comparisons in laboratory settings tend to be less informative about the specific mechanisms at work, there is increasing evidence that active control leads to improved memory beginning at an early age. For instance, active navigation of a spatial environment leads to better memory as early as five years of age (Feldman & Acredolo, 1979; McComas, Dulberg, & Latter, 1997; Poag, Cohen, & Weatherford, 1983). Moreover, this advantage is specific to task-relevant information, consistent with the idea that exploration depends on a constructivist search process that is absent in yoked observation. For example, a study by Cohen and Cohen (1982) examined first and sixth graders' spatial memory for a set of landmarks in a classroom. The landmarks were experienced in one of three ways: simply walking among them, performing unrelated tasks at each station, or performing a set of interrelated tasks that centered on a common theme (e.g., writing and sending a letter). Children in this latter condition had better spatial memory for the locations of the landmarks, regardless of age, suggesting that navigation in the service of a goal supported the formation of spatial memory. In a recent study involving a full control version of the task from Markant et al. (2014; see Figure 1a), Ruggeri, Markant, Gureckis, and Xu (2016) found that control over study led to improved memory for studied items among 6–8-year-old children. Moreover, this advantage remained in a follow-up recognition test after a 1-week delay, providing an important demonstration that the benefits of active control persist beyond the immediate testing situation.

Developmental studies of self-guided study similarly suggest early benefits from active control. Partridge, McGovern, Yung, and Kidd (2015) found that 3–4-year-olds had better memory for novel object–word associations when they chose which objects to learn about during study, as compared to passive observation in which no choices were required. However, as with adults, the ability to efficiently allocate study time appears to develop over the course of childhood (Dufresne & Kobasigawa, 1989; Metcalfe, 2002; Metcalfe & Finn, 2013). For example, Metcalfe (2002) showed that although sixth graders chose to study items based on their pre-existing memory, they were inefficient in controlling how long to study items (in particular, "laboring-in-vain" on words that were unlikely to be learned because of their difficulty). In general, young children's study decisions reflect sensitivity to the strength of their own memories, but the ability to strategically control study is seen to improve over the course of adolescence (see Schneider, 2008 for a review).

A similar distinction is seen in studies on active inquiry in young learners. Recent studies have shown that children can reason about statistical evidence and perform active interventions that facilitate learning (Schulz, 2012; Xu & Kushnir, 2013), that they are efficient in their active information search (Ruggeri, Lombrozo, Griffiths, & Xu, 2015), and that concept learning is more effective when given control over the learning experience compared to yoked observation of the same materials (Sim, Tanner, Alpert, & Xu, 2015). As in the case of adaptive study, however, the ability to use sophisticated intervention strategies (e.g., when reasoning about multivariable systems) develops with more experience in inquiry-based activities (Kuhn & Brannock, 1977; for a review, see Zimmerman, 2000). Although more work is necessary to clarify the roles of the mechanisms described above, these findings demonstrate that active control over learning can enhance both episodic memory and conceptual learning at early stages of development.

Implications for Instruction: Balancing Guidance and Learner Control

Relative to passive observation, our review suggests that active control has positive effects on memory across a wide range of activities and student populations. In particular, research on active exploration lends further support for the use of interactive, simulation-based instruction (De Jong et al., 2013). Controlling how to study and conducting active inquiry can also have a powerful influence on memory and learning but depend more closely on the acquisition of strategies for structuring learning events, which emerge with more experience as an active learner. Instructors should therefore consider whether minimizing student control improves (or normalizes) short-term outcomes at the expense of long-term retention of the material and the ability to learn independently outside of the classroom (Kuhn, 2007).

This trade-off between control and direct instruction poses a constant challenge for educators. What kinds of scaffolding are necessary to ensure understanding and retention of the content while fostering students' ability to learn in a self-directed manner? Some researchers have argued that placing control in students' hands forces them to engage in unnecessary search at the expense of meaningful learning (Kirschner et al., 2006; Mayer, 2004). It seems undeniable that a complete lack of feedback or guidance ("pure discovery," according to Mayer, 2004) will tend to produce poor outcomes for most students and that, more generally, instruction should not impose unwarranted cognitive demands simply to adhere to an idealized vision of active learning. On the other hand, the evidence we have reviewed strongly suggests that a complete absence of control during learning may render even the best direct instruction less memorable.

In our view, instructors can be better prepared to manage this trade-off if they know about the cognitive consequences of different forms of control that are involved in classroom activities, including their effects on memory formation. Although the benefits of active learning have been supported by large-scale comparisons with traditional, passive formats like lectures, there is a great deal of variability in how active instruction is implemented, and it remains unclear how efficacy depends on content domain or individual differences among students (Freeman et al., 2014). Identifying how active learning interacts with episodic memory is an important step toward understanding and predicting its benefits and, as we have noted, one that poses a number of open questions for further basic research.

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NOTE

[1] We use the term *mechanism* throughout this article to describe psychological and situational factors that may

impact learning and memory processes. These include processes within the individual as well as interactions between learners and their environment.

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