Mem Cogn (2016) 44:727–739
DOI 10.3758/s13421-016-0600-4

Effects of dividing attention on memory for declarative and procedural aspects of tool use

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Abstract Tool-related knowledge and skills are supported by a complex set of memory processes that are not well understood. Some aspects of tools are mediated by either declarative or procedural memory, while other aspects may rely on an interaction of both systems. Although motor skill learning is believed to be primarily supported by procedural memory, there is debate in the current literature regarding the role of declarative memory. Growing evidence suggests that declarative memory may be involved during early stages of motor skill learning, although findings have been mixed. In the current experiment, healthy, younger adults were trained to use a set of novel complex tools and were tested on their memory for various aspects of the tools. Declarative memory encoding was interrupted by dividing attention during training. Findings showed that dividing attention during training was detrimental for subsequent memory for tool attributes as well as accurate demonstration of tool use and tool grasping. However, dividing attention did not interfere with motor skill learning, suggesting that declarative memory is not essential for skill learning associated with tools.

Keywords Declarative memory · Procedural memory · Attention · Tool use

As humans, we have developed customized tools for almost every function in our lives, whether it is to shave with a razor, flip an egg with a spatula, or cut paper with scissors. These manufactured tools, which are designed to provide a mechanical advantage in interacting with action recipients, are referred to as *complex tools*. *Simple tools*, in contrast, only amplify the movement of upper limbs (e.g., extending reach with a stick; Frey, 2007; Heilman, 2002). We learn how to use various complex tools throughout our lives and become heavily dependent on them to perform daily activities. Thus, the ability to use such tools is critical for independent living. However, as a result of certain neurological conditions, some people are left unable to use tools that they may have used proficiently in the past. In some cases, these individuals may also be unable to learn how to use new tools to perform new functions. These devastating impairments can impact one's ability to live independently, and it has been shown that a lack of independent living is associated with poor quality of life (Foundas, Macauley, Raymer, & Maher, 1995). Yet we do not have a clear understanding of how people learn to use novel tools and how different aspects of tool-related knowledge and skills are represented in the brain.

The current experiment was conducted as an extension to two previous patient studies that investigated the memory representations of complex tool-related knowledge and skills. In Roy and Park (2010), an individual with hippocampal amnesia, associated with profound declarative memory impairment, was shown to have unimpaired motor skill learning but severely impaired memory for tool attributes and tool grasping. In a subsequent study (Roy, Park, Roy, & Almeida, 2015), patients with Parkinson's disease, associated with striatal dysfunction and procedural memory impairment, were found to have impaired motor skill learning, but intact memory for tool attributes and tool grasping. Interestingly, skilled use of a tool to a command was impaired in both patient groups. Taken together, these two studies present evidence of double dissociation of the

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memory representations underlying tool knowledge and skills. Specifically, they suggest that memory for tool attributes and tool grasping is primarily declarative, whereas motor skill acquisition and skilled tool use may involve an interaction of both declarative and procedural memory systems. However, the nature of these interactions and the relative contribution of each memory system are still unknown. Furthermore, findings from these studies are based on performance of individuals with damage to particular memory systems (i.e., amnesia, Parkinson's disease [PD]). Thus, it is unclear how tool-related knowledge and skills are represented in healthy, cognitively unimpaired individuals and whether these representations are consistent with earlier patient studies. The current study investigated memory for tool knowledge and skills in a healthy sample of individuals using a divided attention paradigm as a means of selectively interfering with declarative memory processes. A brief review of human memory systems, memory representations of tool-related knowledge and skills, and effects of divided attention on memory is provided, followed by an overview of the current study.

Human memory systems

It is generally accepted that memory is not a unitary construct but that there are multiple memory systems represented in different parts of the brain (see Squire, 2009). The most common distinction is made between declarative memory and procedural memory. *Declarative memory* includes knowledge that is often consciously retrieved and it includes both semantic (i.e., general knowledge) and episodic (i.e., recollection of personal experiences) memory. Declarative memory is believed to rely on the medial temporal lobes, including the hippocampus and related structures (Moscovitch, Nadel, Winocur, Gilboa, & Rosenbaum, 2006). *Procedural memory*, in contrast, is a form of nondeclarative memory that is involved in incremental learning of motor skills and cognitive habits (Squire, 2009). Procedural learning is believed to take place implicitly, without demands for attentional resources (Reber, 1993). Although it is believed that the frontal-striatal system plays a critical role in supporting procedural memory, other brain regions, such as the cerebellum, have also been implicated (see Doyon et al., 2009; Penhune & Steele, 2012; also see Shohamy, Myers, Kalanithi, & Gluck, 2008). Thus, declarative and procedural memory systems are anatomically and functionally dissociable (see Knowlton, Mangels, & Squire, 1996).

Although early memory research tended to investigate each memory system in isolation based on the assumption that they are distinct, a growing body of research suggests that the two systems may function interactively. The nature of the interaction appears to vary as well. Studies have provided evidence for *cooperative* interaction, *competitive* interaction, and *compensatory* interaction between the two systems. It has been proposed that the two systems are cooperative, or complementary, in that they are both required, but each system has a different role in supporting performance (McClelland, McNaughton, & O'Reilly, 1995). Evidence of a competitive relationship between declarative and procedural memory can be found in the domain of motor skill acquisition. It has been argued that whereas motor skill acquisition is primarily mediated by procedural memory, the declarative memory system may interfere with procedural learning in early stages of learning (Brown & Robertson, 2007). Last, in a compensatory interaction, the system that typically mediates performance is compromised, and the intact system is recruited to support performance (Moody, Bookheimer, Vanek, & Knowlton, 2004). Thus, the concept of two fully independent memory systems may be outdated, and recent research suggests that the nature of interaction between the two systems actually varies across different domains and forms of learning (for a review, see Foerde & Shohamy, 2011).

Memory representations of tool-related knowledge and skills

Declarative memory and tools

Learning how to use a novel complex tool requires one to learn about characteristics of the tool (e.g., perceptual features of the tool, knowledge of its function, how it is grasped). Previous research suggests that information about tools and their properties depend on regions associated with declarative memory (Roy & Park, 2010; Warrington & Shallice, 1984; Weisberg, van Turennout, & Martin, 2007). Individuals with medial temporal lobe damage are impaired in their memory for object-specific information (Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Warrington, 1975). The declarative memory system has also been shown to be critical in mediating tool grasping for use (Creem & Proffitt, 2001; Creem-Regehr & Lee, 2005; though, see Goldenberg & Spatt, 2009). In a behavioral study, Creem and Proffitt (2001) showed that healthy participants were less likely to grasp familiar tools appropriately, by their handles, when they concurrently performed a semantic secondary task compared to when they performed a visuomotor secondary task. The authors concluded that grasping a tool for the purpose of using it, but not simply moving it, requires semantic knowledge about the tool. In a subsequent neuroimaging study, Creem-Regehr and Lee (2005) reported greater activation in the middle temporal gyrus and fusiform gyrus for images of familiar tools with handles compared to unfamiliar graspable shapes, suggesting that functional knowledge of tools influences neural representations associated with grasping the tool for use. In Roy and Park (2010), an amnesic individual, who was trained to use a set of novel complex tools, was severely impaired in his ability to recall the proper manner of grasping for these tools when subsequently tested. Thus, previous research with both novel and familiar tools suggests that grasping a tool in order to use it requires declarative knowledge of the tool.

Procedural memory and tools

It is generally accepted that motor skill learning relies primarily on the procedural memory system. It is believed that the basal ganglia and related structures, particularly the striatum, play a critical role in supporting motor skill acquisition and retention (Doyon et al., 2009). Disease of these brain regions has been associated with impaired procedural memory. Individuals with Parkinson's disease are impaired on procedural memory tasks, such as probabilistic classification learning and motor sequence learning (Knowlton et al., 1996; Siegert, Taylor, Weatherall, & Abernethy, 2006; Wilkinson, Khan, & Jahanshahi, 2009). Conversely, a study with the famous amnesic individual, H. M., showed that while he had profound declarative memory impairment due to medial temporal lobe damage, he was able to learn how to use a stylus to perform a mirror tracing task. He became progressively faster on this task and retained performance on this task even after 1 year (Corkin, 1968; Gabrieli, Corkin, Mickel & Growdon, 1993). Nonetheless, there is some debate regarding the role of declarative memory in motor skill learning.

Interaction of declarative and procedural memory and tools

Some investigators have argued that motor skill learning may involve a competitive interaction of declarative and procedural memory. In this interaction, declarative memory competes with procedural memory during early stages of motor skill learning and creates a naturally occurring impediment in learning. Similarly, when the declarative system is disengaged from the process, motor skill learning is enhanced (Brown & Robertson, 2007). Others have argued that declarative memory has a facilitative role in early stages of motor skill learning and that a cooperative interaction of both systems is required (see Penhune & Steele, 2012). There is also evidence of a compensatory interaction in which the declarative system may become more involved in supporting motor skill learning when the procedural system is compromised (Gobel et al., 2013). Thus, although procedural memory may have the primary role in mediating motor skill learning, declarative memory may be involved in some capacity during early learning. The precise nature of this interaction between the two memory systems requires further investigation.

In addition to motor skill learning, it has been proposed that skilled tool use (i.e., intentional tool use) relies on a cooperative interaction of both declarative and procedural memory systems (Negri, Lunardelli, Gigli, & Rumiati, 2007; Roy et al., 2015; Silveri & Ciccarelli, 2009). In Roy and Park (2010), an amnesic individual, D. A., showed unimpaired motor skill acquisition associated with novel complex tools but was unable to demonstrate the use of these tools to command. Yet, when the tool's recipient (i.e., the object that the tool acts on) was positioned in its appropriate starting location by the experimenter, his ability to use the tools improved remarkably. This finding suggests that declarative memory is critical for recalling contextual information related to the task, whereas procedural memory is critical for skilled enactment of the motor skill. Individuals with PD were tested in a similar experiment in which they were trained to use a set of novel complex tools and were subsequently tested on their ability to demonstrate tool use to command (Roy et al., 2015). Results showed that while participants with PD had no difficulty in performing components of the tasks accurately, they did not retain their speed of task completion after a 3-week delay. Based on these two patient studies, it could be argued that skilled tool use relies on a cooperative interaction of both declarative and procedural memory systems.

Effects of dividing attention on memory

Effects of dividing attention on declarative memory

The general consensus in the literature is that encoding information into declarative memory requires attentional resources and that dividing attention at study has a negative effect on subsequent declarative memory performance (Fernandes & Moscovitch, 2013). It is believed that both primary and secondary tasks compete for common attentional resources, which disrupts encoding of new associations into declarative memory. Medial temporal lobe structures, along with regions in the prefrontal cortex, are involved during encoding (Chun & Turk-Browne, 2007). The majority of research investigating effects of divided attention on declarative memory involves learning of verbal stimuli (e.g., list learning). Few studies have examined the effects of divided attention on memory for skilled actions or knowledge related to tools. Research in our lab has studied the effects of divided attention on learning of novel naturalistic actions (NNAs), which are arts and crafts type of tasks involving use of everyday objects to create an end product (e.g., building a mock volcano using a plastic bottle, baking soda, and other objects). Results showed that dividing attention when participants were viewing a video demonstration of the NNA task impaired the ability of participants to construct the viewed NNA from memory in comparison to the full attention condition. Based on these findings, it was argued that encoding the steps associated with performing an NNA requires declarative memory (Gold & Park, 2008).

Effects of dividing attention on procedural memory

The effects of divided attention on procedural memory are not well understood at this time, and findings on the attentional demands of procedural learning have been mixed. Early researchers in this area showed a decrement in motor sequence learning under divided attention and attributed this impairment to a lack of sufficient attentional resources (Nissen & Bullemer, 1987). This argument was subsequently challenged, and it was proposed that it is not learning per se that is affected by dividing attention; rather, performance or behavioral expression of the learned skill is affected. It was demonstrated that when a skill trained under divided attention was subsequently enacted under full attention, performance was equivalent for both full and divided attention conditions (Frensch, Lin, & Buchner, 1998). Although the serial reaction time task (SRTT) is perhaps the most widely used primary task in these studies, studies using other procedural learning tasks, such as pursuit rotor and probabilistic classification learning tasks, have shown that performance, and not learning, was affected by dividing attention (Eysenck & Thompson, 1966; Foerde, Poldrack, & Knowlton, 2007).

In some circumstances, dividing attention may also enhance motor learning. It has been suggested that features of the secondary task influence whether motor sequence learning will be impaired or enhanced. A study showed that participants retained a perceptual-motor task better under difficult rather than easy dual-task conditions (Roche et al., 2007). The authors argued that the more difficult secondary task mobilized greater attentional resources. Motor sequence learning may also be enhanced when the secondary task is similar in nature to the primary task. Findings from one study suggested that when the primary and secondary tasks draw on common cognitive processes, skill learning is enhanced, whereas when they rely on different cognitive processes, skill learning is impaired (Goh, Sullivan, Gordon, Wulf, & Winstein, 2012). Thus, the effects of dividing attention on procedural memory are complex and warrant further study, especially given the lack of research with tool-related skilled actions.

Overview

As described earlier, it has been proposed that memory for tool properties is primarily mediated by declarative memory processes, and motor skill learning is primarily dependent on procedural memory. It has also been suggested that motor skill learning and skilled tool use may rely on an interaction of both memory systems. Specifically, it was argued that skilled tool use relies on a cooperative interaction of both declarative and procedural memory systems. With respect to motor skill learning, the degree to which declarative memory is involved is unclear. Dividing attention is believed to selectively disrupt encoding of new information into declarative memory. Therefore, this behavioral technique may be useful in determining whether or not encoding of declarative task knowledge is critical during motor skill learning with complex tools. To our knowledge, no previous studies have directly investigated the effect of dividing attention on learning of motor skills and knowledge associated with complex tools. Findings regarding memory representations of other aspects of tool knowledge and skills (i.e., tool features, skilled tool use) were largely consistent across our two earlier patient studies discussed; however, it is important to note that these previous findings are based on patient performance. As such, the degree of generalizability to a healthy population is not known. Thus, if converging evidence were obtained in a healthy population, it would provide additional support of the proposed roles of declarative and procedural memory in mediating tool-related knowledge and skills.

The current study investigated the nature of interaction between declarative and procedural memory on tool-related knowledge and skills with the use of a dual-task paradigm. Healthy younger adults were trained to use a set of novel complex tools by viewing a brief video demonstrating correct performance of all aspects of the task. Subsequently, their memory for tool features (e.g., function, color), tool grasping, and skilled tool use to command was tested. Some of the tools were trained under divided attention as a means of disrupting encoding of declarative information related to tools and their uses. In general, it was expected that divided attention during training would be detrimental for memory of any aspect of tool-related knowledge that relied on declarative memory, but that there would be no impact on aspects supported primarily by procedural memory. Four hypotheses were tested in the current study:

1. Motor skill learning is believed to be a form of procedural memory and should therefore not be impaired by dividing attention. Specifically, it was hypothesized that the rate of motor skill learning associated with complex tools, as assessed by training completion time, would not differ between full and divided attention conditions. Based on findings from Roy and Park, it is reasonable to believe that declarative memory is not required for motor skill learning. However, given the lack of consensus among previous studies, it is possible that motor skill learning may suffer if encoding of task knowledge is disrupted by dividing attention which would be reflective of a cooperative interaction of declarative and procedural memory systems. It is also possible that motor skill learning involves a competitive interaction between these memory systems. If so, it would be expected that skill learning would be faster in the divided attention condition compared to full attention.
2. Recall of tool features should be impaired for tools that were trained under divided compared to full attention.

This hypothesis is based on research showing that dividing attention is detrimental to learning of declarative information (e.g., Iidaka, Anderson, Kapur, Cabeza, & Craik, 2000) and findings from Roy and Park (2010).

3. Demonstration of tool grasping should be impaired for tools trained under divided compared to full attention based on research showing that tool grasping has a strong declarative component (Creem & Proffitt, 2001; Roy & Park, 2010).
4. It is argued that tool-use accuracy relies on encoding of task-related details and should therefore be impaired for tools trained under divided compared to full attention. However, if these task-related details are successfully encoded, allowing for accurate tool use, there should be no difference in completion time between attention conditions. This hypothesis is based on the previous findings suggesting that skilled tool use relies on a cooperative interaction of both memory systems, such that declarative memory mediates recall of knowledge related to using a tool and procedural memory mediates motor efficiency of tool use.

Method

Participants

Thirty-two younger adults (22 females, 10 males) between the ages of 18 and 33 years (*M* = 23.81 years, *SD* = 3.88 years) participated in the current study. Participants were recruited and tested at York University in Toronto, Canada. They were recruited through the York University undergraduate research pool and through flyers posted in various locations on campus. Participants from the research pool were granted course credits for their participation, and participants who responded to flyers were offered a nominal amount of monetary compensation. All participants were required to be right-handed, fluent in spoken and written English (learned English by age 5), and have at least 12 years of education. Exclusion criteria included color-blindness, past head injury resulting in loss of consciousness, and any psychological, neurological, or serious medical illness that could potentially affect cognition or motor performance. The experiment was approved by the ethics review board at York University, and each participant provided written consent prior to participation.

Materials

Novel tools Twelve novel complex tools were constructed from K'NEX, a commercial children's construction toy (see Fig. 1). These 12 tools were divided into four sets of three tools each (Sets A, B, C, and D). The tools used in the current study were a subset of 15 tools that were developed by Roy and Park (2010). Each tool was designed to perform a specific function by interacting with a unique action recipient (e.g., guide a wheel down a curved path). Tools were designed to be used unimanually, with the right hand, and each tool task involved a distinct motor skill. As demonstrated in Roy and Park (2010), the tools were designed in such a manner that their function, manner of use, and manner of grasping could not be determined from physical appearance. Each tool was painted a different solid color. A set of tests was also developed to assess memory for various aspects of the tools (e.g., knowledge of the tool's function, manner of grasp). A brief training video was created for each tool, demonstrating how the tool is grasped, how it is manipulated, and how the task is performed from start to finish. Each video also contained an audio track that provided verbal descriptions of the task. Further details on these materials, and the tests developed to assess performance described next, can be found in Roy and Park (2010).

Recall test A set of gray-scale images of the tools was used to develop a recall test of tool attributes. Three photographs of each tool were taken from three different, approximately equidistant, angles. During the recall test, participants were shown the three pictures of each tool, one tool at a time, and were asked to answer the following five questions about each tool: (1) What is the function of the tool/What is it used for? (2)

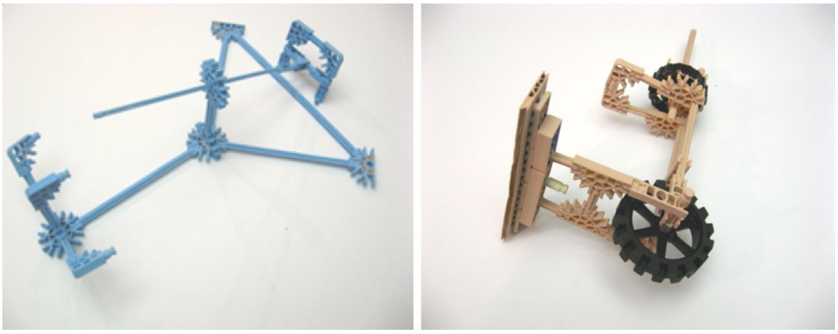

Fig. 1 Examples of novel complex tools used in the current experiment

What is the color of the actual physical tool? (3) What is the recipient that the tool interacts with? (4) What is the color of the recipient? and (5) How many recipients does the tool act on? Participants were asked to verbally provide their responses, which the experimenter recorded verbatim.

Grasp-to-command test Each tool was placed on the table in front of the participant without its associated recipient(s). The participant was instructed, "With your right hand, show me how you would grasp this tool if you were to use it. Show me the first thing that comes to mind." The participant was allowed to rotate the tool in order to make the handle more accessible. After the participant demonstrated the grasp, the participant was asked to release the tool.

Use-to-command test After the participant demonstrated the grasp of a tool, the experimenter set up the entire task with all associated materials. The tool was positioned in front of the participant in the proper orientation for use, and the recipient(s) was placed in a small outlined square, to the left of the tool. The participant was instructed, "Again, using your right hand, I'd like you to show me how you would use the tool." Participants were expected to first position the recipient in the correct starting location. Then, they were given a limit of 60 seconds to demonstrate correct use of the tool from start to finish. Timing began when the tool made contact with the recipient and ended when either the task was completed without error or when the time limit was up.

Lag-1 task An auditory lag-1 task was created. The lag-1 task was chosen as a secondary task as it has been shown to draw on working memory and attentional processes (see Dobbs & Rule, 1989). In this lag-1 task, an audio file of spoken numbers was played on a laptop. During pilot testing, it was determined that a lag-1 task, presented at a 2-second rate (i.e., one number every 2 seconds) was sufficiently challenging without overwhelming participants. In the task, participants were told to repeat out loud the number that preceded the last number they heard. For example, for the sequence, "5......6......2....," after hearing "6," the participant would say "5." In total, 10 lag-1 files were created, each with a different, random, sequence of numbers. One of these files was 20 seconds in length and was used as a practice file. The other nine files were each 5 minutes in length and were used during training of tool tasks.

Design and procedure

Each participant was tested individually in a single session lasting approximately 90 minutes. The session was composed of two phases: training and test. Half of the tools were trained under full attention (FA) as in the traditional manner of performing the tasks (see Roy & Park, 2010), and the other half were trained under divided attention (DA). Thus, each participant was trained in both FA and DA conditions. Participants were trained to use all 12 tools (i.e., all four sets), one tool at a time. As an example, as shown in Appendix, Participant 1 was trained on sets A and B under FA and on sets C and D under DA. Out of the two sets in each attention condition, one set (e.g., Set A) was trained over four consecutive trials (i.e., T1, T2, T3, and the probe trial) to provide a measure of training performance. The other tool set (e.g., Set B) served as the test set and was trained on a single trial.[1] The combination of attention conditions and tool sets resulted in four training conditions (i.e., FA–training set, FA–test set, DA–training set, and DA–test set). The order of these training conditions was fully counterbalanced across participants. It should be noted that all components of the test phase were conducted under full attention for all participants (see Appendix for experimental design).

Training At the start of the session, participants were given instructions for the lag-1 task and were given a brief practice trial with a 20-second lag-1 file. Errors were corrected and, if necessary, instructions were repeated to ensure that participants fully understood the task. After the practice trial, one of the other eight lag-1 files was played at random, and the participant performed the lag-1 task for the first 60 seconds of the clip. This 60-second trial served as the pretraining measure of performance on the lag-1 task.

After measuring pretraining performance on the lag-1 task, participants were given practice on the tool tasks. Before beginning with the 12 experimental tools, participants were given two practice training trials, one for each attention condition, with two different tools. These tools had no similarity to the 12 experimental tools (e.g., different colors, functions, manner of grasp). Before proceeding to the experimental training trials, it was ensured that participants understood all instructions, and clarification was provided if necessary. During training of a tool task, participants were told that they would have up to 60 seconds to try and perform each tool task in the same way as it had been performed in the video as quickly as possible, without making any errors, and that they should restart the task if they made an error.

Before training with each tool, a divider was placed on the table to hide the tool and its associated recipient(s) from the participant's view. However, a small section of the divider in front of the participant's right hand was cut out. The participant's right hand came through this small space and rested on the table throughout the duration of the training phase. The experimenter placed the tool into the participant's right hand

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[1] During pilot testing, it was found that four consecutive training trials countered the effects of dividing attention on the subsequent recall test. The effects of dividing attention appeared to diminish after repeated exposure to tool attributes over trials. For this reason, tools presented in the test phase were only given a single training trial.

and positioned the participant’s fingers in the correct configuration for use. Thus, participants could feel the tool but could not yet see it. The tool was hidden from view to prevent participants from visually encoding physical attributes of the tool before beginning the task, especially as this initial set-up procedure takes place without the secondary task in the divided attention condition. The purpose of configuring grasp on the tool prior to the video was to allow the participant to begin the task immediately after watching the video. Participants were instructed to continue to grasp the tool until they had completed training with that particular tool. Once the participant’s hand was positioned on the tool, the experimenter verbally described the type of errors that could be made in the task, which would require the participant to restart the task (e.g., “In this task, if the recipient falls off the tool onto the table, the task has to be restarted”). However, these descriptions did not provide any specific information about the tool’s use or its features. Although these details are normally provided in the tool videos, the videos were muted for this experiment to prevent auditory interference with the lag-1 task.

After receiving instructions about potential task errors, participants viewed the associated training video, with the tool and its recipient(s) still hidden from view. Participants were instructed not to maneuver the tool, or try to perform the task, while the video was playing. Immediately after the video finished playing, the experimenter removed the divider and gestured for the participant to begin the task. Timing began when the tool made contact with the recipient and ended once an errorless trial was completed, or when the 60-second time limit was up. Once the participant had completed training with a tool, the experimenter removed it from the table, placed the cardboard divider back on the table, and positioned the next tool into the participant’s right hand.

Training in the DA condition was the same as in the FA condition except that there was a lag-1 secondary task, which started immediately prior to the training video, before the divider was removed. Participants were instructed to stop performing the secondary task either after completing the task successfully or when the 60-second time limit elapsed if they were unable to complete the task. Participants were encouraged to do their best on both the lag-1 task and the tool task, but to treat the lag-1 task as the more important task in order to draw attention away from the tool task. A different lag-1 set was selected for each of the six tools in the DA condition. For the training set, in which tools were trained over four consecutive trials, the lag-1 task was turned off after Trial 3, and the task was performed one more time under full attention for the probe trial. For the test set, in which tools were trained on a single trial, the lag-1 task was turned off once the trial was completed and all materials related to the tool were removed from the participant’s view.

The experimenter did not provide any verbal feedback to participants during training in order to limit interference in the DA condition. However, participants were instructed beforehand that the experimenter would tap on the desk if the participant made an error and did not restart the task. This gesture would signal the participant to start over. Also, participants were informed before the introduction of each tool whether it would be trained under FA or DA and whether it would be trained over four trials or one trial.

After completing training of the 12 tools, all participants performed the lag-1 task on its own to assess posttraining performance. The remaining lag-1 file was played, and participants performed the task for 60 seconds. After performing the lag-1 task, participants were given a 3-minute break during which they worked on a dinosaur word search as a distracter task. The purpose of this distracter task was to give the participant a brief break from the experiment and to keep them engaged with a pleasant but unrelated task.

Test After completing the training phase, the test phase was administered, which included the recall, grasp-to-command, and use-to-command test measures. Only tools that were given a single training trial (i.e., test set) during training were included in the test phase. Thus, three tools from the FA condition and three tools from the DA condition were included in the test (see Appendix).

Scoring and statistical analyses

The following scoring procedures were implemented for all measures. Interrater reliability is also presented for measures that do not have an objective scoring system and therefore may have required experimenter judgment. Interrater scores reflect the percentage of agreement between the two raters for a given measure. Further details on scoring procedures can be found in Roy and Park (2010).

Two aspects of training performance were recorded: completion time and number of errors. Completion time reflects the time of the single errorless attempt, from the moment the tool made contact with receipt to successful completion of the task. If a participant was unable to complete the task successfully within 60 seconds, a maximum score of 60 seconds was recorded. The number of errors made during each task was tallied.

Performance on the recall test was measured as the percentage of correct responses to items in each test trial. Recall items were divided into two conceptual categories, *functional associative* and *perceptual*. This classification is based on earlier research by Warrington and Shallice (1984) that distinguished between functional associative and perceptual features of living and nonliving objects. This classification was also used to report detailed results on recall data in Roy and Park (2010). The functional associative category included functionally relevant tool features including function of the tool and the identity of the recipient on which it performs the function. In contrast, perceptual recall items referred to incidental physical attributes, such as tool color, recipient color, and number of recipients. During initial development of the novel tools and associated memory tests, a pilot study was conducted with a sample of healthy younger adults to refine the memory measures. Based on the responses provided by these participants, a scoring rubric of acceptable responses for the recall test was developed and has been used in subsequent studies with these tools (Roy & Park, 2010; Roy et al., 2015).

Grasp-to-command performance was scored as the percentage of correct grasp demonstrations to command in each test trial. Each correct demonstration was given one point. As described earlier, each tool has a unique functional manner of grasping that participants learn during the training phase. A second independent rater scored 30 % of the data, and an interrater reliability score of 94.9 % was obtained for grasp-to-command.

Performance on the use-to-command test can be broken down into two components, accuracy and completion time. Tool use accuracy was measured as the percentage of correct tool use demonstrations to command (i.e., whether or not a participant was able to complete the task successfully within 60 seconds), whereas completion time provided a measure of how quickly the participant was able to complete the task, in seconds. In terms of accuracy, if a participant was able to accurately demonstrate the tool's use within the 60-second time limit, the demonstration was scored as correct, and one point was given. If the task was performed incorrectly, or was not completed within the 60-second time limit, the demonstration was marked as incorrect and a score of zero was given. A second independent rater scored 30 % of the data, and an interrater reliability score of 98.3 % was obtained for use-to-command accuracy. Completion time for use-to-command performance was measured in the same manner as in training.

Parametric statistics were used to analyze all measures of performance. Analysis of motor skill acquisition was based on tools trained over four trials during training. Analysis of all other measures, including recall of tool attributes, grasp-to-command, and use-to-command, was based on tools trained on a single trial (i.e., the test set). All pairwise comparisons were performed using Bonferroni correction, and raw, unadjusted, *p* values are reported.

Results

Baseline performance

To ensure that tool attributes, proper manner of grasping, and proper manner of use could not be inferred by either appearance or handling of the tools, a brief baseline study was conducted prior to the current experiment. Baseline performance of all measures was obtained from a separate sample of 20 younger adults (8 males, 12 females) between the ages of 18 and 26 years ($M = 20.6$ years, $SD = 2.56$ years). As expected, participants were unable to accurately recall the attributes or demonstrate the skills associated with the tools (see Table 1). Thus, improved performance in the current study can be attributed to learning that occurred during the training phase.

Training

Completion time Figure 2 shows average completion time across training trials (T1, T2, T3) for tools trained under DA and FA. Trials in which participants did not complete the task (i.e., maximum time scores) were removed before conducting analyses to prevent inflation of scores. Across all trials, 7.2 % of trials were removed from the FA condition, and 8.3 % of trials were removed from the DA condition. A one-way within-subjects ANOVA showed that overall completion time was also slower for tools in the DA condition than in the FA condition, $F(1, 31) = 5.78$, $p = .022$, $\eta^2 = .16$. Linear regression analysis was conducted using the slopes of individuals across T1, T2, and T3 for tools trained under DA and FA conditions. Participants became significantly faster in using tools in the FA condition at a rate of 3.39 s per trial ($SE = .88$ s), $R^2 = .14$, $F(1, 94) = 14.87$, $p < .001$, with a *y*-intercept of 24.02 s ($SE =$ 1.90 s). They became significantly faster in using tools in the DA condition at a rate of 4.22 s ($SE = 1.11$ s) per training trial, $R^2 = .13$, $F(1, 94) = 14.39$, $p < .001$, with a *y*-intercept of 31.10 s ($SE = 2.40$ s). The rates of completion time for tools trained under DA ($M = -4.22$ s, $SD = 3.51$ s) and FA ($M = -3.38$ s, $SD = 3.05$ s) did not differ, $t(31) = .97$, $p = .34$, $\eta^2 = .03$. In summary, participants were slower overall in the DA condition compared to the FA condition; however, the rate of learning was equivalent in the two conditions.

As described earlier, the purpose of the probe trial was to distinguish between effects of divided attention on performance versus learning. A paired samples *t* test on the probe trial completion time showed no difference between tools trained under FA ($M = 15.21$ s, $SD = 6.43$ s) and tools trained under DA ($M = 16.68$ s, $SD = 5.26$ s), $t(31) = -.91$, $p = .37$, $\eta^2 = .03$. Thus, although dividing attention slowed performance in the DA condition in T1, T2, and T3, it did not affect learning of the motor skills.

Table 1 Baseline Performance on Test Measures

Test Measure	*M*	*SD*
Total recall (%)	2.92	3.10
Grasp-to-command (%)	2.50	5.47
Use-to-command		
Accuracy (%)	0.00	0.00
Completion time (seconds)	60.00	0.00

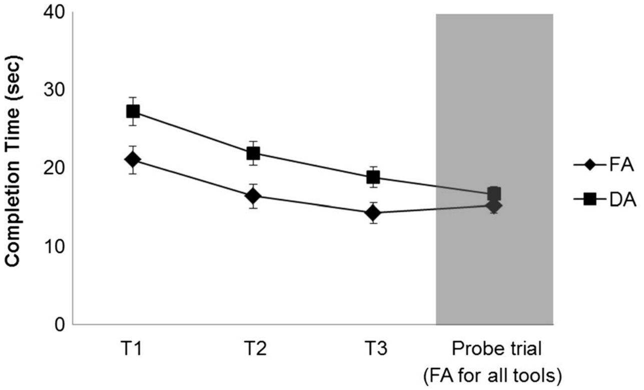


Fig. 2 Mean completion time (+/- *SE*) across training trials (T1, T2, T3, and Probe trial) for tools trained under full attention (FA) and divided attention (DA)

Accuracy A two-way repeated-measures ANOVA with attention condition (FA vs. DA) and trial (T1, T2, and T3) as within-subjects factors showed no significant interaction on error production. There was also no main effect of attention condition on overall error production across trials. However, there was a main effect of trial, showing that participants made fewer errors across trials (T1: *M* = 1.01 errors, *SD* = .71 errors; T2: *M* = .64 errors, *SD* = .66 errors; T3: *M* = .67 errors, *SD* = .69 errors), F(2, 62) = 5.64, *p* = .006, η^2 = .15. Pairwise comparisons showed that the average number of errors was significantly higher in T1 compared to both T2, *t*(31) = 2.93, *p* = .006, η^2 = .22 and T3, *t*(31) = 3.93, *p* < .001, η^2 = .33. Average number of errors did not differ between T2 and T3. Error analysis for the probe trial, which was conducted in a separate paired-samples *t* test, showed that the average number of errors in the probe trial was significantly higher in the DA condition (*M* = .76 errors, *SD* = .80 errors) than in the FA condition (*M* = .36 errors, *SD* = .58 errors), *t*(31) = -2.22, *p* = .034, η^2 = .14. In summary, although there was no significant difference in completion times between the two attention conditions in the probe trial, participants made more errors in the DA than in the FA condition.

Lag-1 task A paired-samples *t* test was conducted to compare pre-training (*M* = 98.89 %, *SD* = 2.86 %) and posttraining (*M* = 97.56 %, *SD* = 3.98 %) accuracy on the lag-1 task. Accuracy did not differ between these two time points, *t*(31) = 1.92, *p* = .07, η^2 = .11. A paired–samples *t* test was also conducted to compare the average lag-1 percent accuracy performed during DA (i.e., T1, T2, and T3; *M* = 73.50 %, *SD* = 11.49 %) and during FA (i.e., pre- and posttests; *M* = 98.23 %, *SD* = 2.85 %). Accuracy on the lag-1 task was significantly lower during DA than during FA, *t*(31) = 13. 04, *p* < .001, η^2 = .85. Last, a repeated-measures ANOVA showed that lag-1 accuracy improved across lag-1 training trials, *F*(2, 62) = 7.57, *p* = .001, η^2 = .20. Thus, dividing attention had a negative impact on performance of the secondary task, but there was some improvement across trials.

Use-to-command

Completion time As with the training analyses, maximum time scores were removed before conducting analyses on use-to-command completion time. There was no significant difference in use-to-command completion time between tools trained under FA and DA, *t*(31) = -.21, *p* = .83, η^2 = .001 (see Fig. 3). In summary, although use-to-command accuracy was worse for tools trained under DA relative to FA, when looking only at correctly performed use-to-command attempts, there is no effect of dividing attention on completion time.

Accuracy A paired-samples *t* test showed that use-to-command accuracy was significantly worse for tools trained under DA relative to FA conditions, *t*(31) = 3.69, *p* = .001, η^2 = .31 (see Fig. 3).

Recall accuracy

A two-way repeated measures ANOVA was conducted with attention (FA vs. DA) and recall category (functional associative vs. perceptual) as factors and percentage accuracy as the

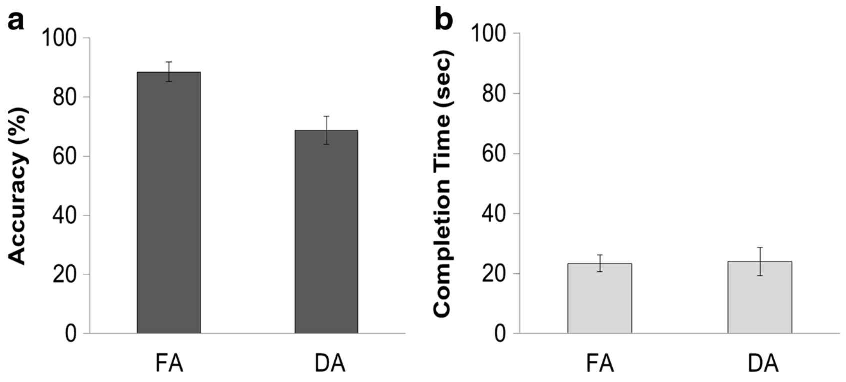


Fig. 3 Use-to-command accuracy (A) and completion time (B) in the test phase for tools trained under DA and FA. A. Percentage of correct use-to-command demonstrations (+/- *SE*). B. Mean completion time of correct use-to-command demonstrations (+/- *SE*)

dependent variable (see Fig. 4). There was no significant interaction between attention condition and recall category on accuracy. However, there was a main effect of attention condition showing lower overall recall accuracy for tools trained under DA compared to FA, $F(1, 31) = 8.78$, $p = .006$, $\eta^2 = .22$. There was also a main effect of recall category showing that participants had higher recall accuracy for functional associative details about tools than perceptual details, $F(1, 31) = 185.34$, $p < .001$, $\eta^2 = .86$.

Grasp-to-command

Grasp-to-command accuracy for tools trained in the two attention conditions was analyzed using a paired-samples *t* test. Grasp-to-command demonstration was significantly worse for tools trained under DA ($M = 11.46$ %, $SD = 21.77$ %) than tools trained under FA ($M = 35.42$ %, $SD = 31.61$ %), $t(31) = 3.47$, $p = .002$, $\eta^2 = .28$.

Discussion

The current study investigated the contributions of declarative and procedural memory in mediating various aspects of tool-related knowledge and skills. Participants were trained to use a set of novel complex tools under full or divided attention and were subsequently tested on their recall for various aspects related to these tools (e.g., tool attributes, tool grasping, and tool use). In general, it was expected that dividing attention during training would be detrimental for any aspects of tool-related knowledge dependent on declarative memory. Components of tool-related knowledge and skills that do not rely on declarative memory were expected to be unaffected by dividing attention during training. Overall, current findings obtained with healthy adults provide converging evidence for results of our previous patient studies.

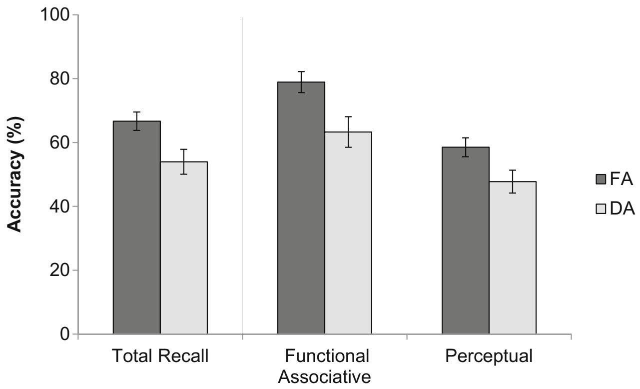


Fig. 4 Percentage of correct responses (+/- *SE*) for recall of test items for tools trained under full attention (FA) and divided attention (DA)

Motor skill learning

It was hypothesized that motor skill learning is primarily mediated by procedural memory processes and, therefore, would not be negatively affected by dividing attention with a secondary auditory lag-1 task. Results showed that, aside from overall slowing, there was no effect of dividing attention on rate of motor skill learning across training trials. There was also no difference in completion time between DA and FA conditions in the probe trial, when the secondary task was removed. These findings are consistent with previous research showing that performance, but not learning, is affected by dividing attention (Frensch et al., 1998; also see Kantak & Winstein, 2012). This result is also consistent with previous research suggesting that motor skill acquisition is primarily mediated by the procedural memory system and that it does not require declarative memory or attentional resources (Gabrieli et al., 1993; Roy & Park, 2010; Song, Howard, & Howard, 2007). Thus, motor skill learning associated with complex tools does not appear to rely on a cooperative interaction of both memory systems. However, analysis of error patterns does raise the possibility of a competitive, or inhibitory, role of declarative memory during procedural motor skill learning. Participants made more errors in the probe trial for tools trained under DA compared to FA. It is possible that in the DA condition participants had adopted a procedural learning strategy during the first three trials but then attempted to perform the tasks consciously in the probe trial, drawing on episodic memory of the task. This hypothesis is consistent with the notion of transfer appropriate processing, which proposes that performance is enhanced to the extent that the cognitive processes during encoding match those required during test (Morris, Bransford, & Franks, 1977).

Previous studies have shown that introducing a secondary task can enhance motor skill learning (Goh et al., 2012; Roche et al., 2007). In the current study, although performance was not enhanced by dividing attention, removal of the secondary task in the DA condition was associated with a higher number of errors than in the FA condition. Therefore, current findings suggest that declarative and procedural memory systems may compete during motor skill learning, such that declarative memory and associated attentional processes can disrupt enactment of procedural skills.

Skilled tool use

Skilled tool use was broken down into two components: accuracy and completion time. The accuracy measure assessed whether or not the task was performed correctly within the time limit, regardless of how quickly the participant performed the task. In contrast, completion time assessed how quickly participants were able to perform correctly completed tasks. It was hypothesized that skilled tool use relies on a cooperative interaction of both declarative and procedural memory systems. This hypothesis is based on previous studies showing that disruption of either declarative or procedural memory leads to impaired skilled tool use (Roy & Park, 2010; Roy et al, 2015). More specifically, it has been proposed that declarative memory may be required for encoding of task-related details (e.g., recipient placement, sequence of steps) required for accurate tool use, whereas procedural memory mediates motor adeptness of tool use (i.e., completion time). Thus, provided participants are able to accurately recall details of the task from declarative memory, completion times should be unaffected by dividing attention. Consistent with these predictions, participants showed lower tool use accuracy for tools trained under DA compared to FA. In addition, tool use completion time for accurately performed tasks was unaffected by dividing attention during training. Thus, current findings provide evidence of a cooperative interaction of memory systems in skilled tool use in a healthy population. Taken together with training data, current findings suggest that motor skill acquisition primarily relies on procedural memory, and may be disrupted by involvement of declarative memory, whereas skilled tool use requires involvement of both memory systems. Therefore, although motor skill acquisition and skilled tool use essentially involve performance of the same task, the role of different memory systems varies across these two aspects of tool-related skilled action.

Recall

It was predicted that dividing attention during training would negatively affect accuracy on a subsequent memory test of tool attributes. Results showed that total recall of tool attributes was significantly lower for tools trained under DA versus FA. Tool attributes were divided into two categories, functional associative and perceptual. The same pattern was found for both functional associative (i.e., tool function and recipient identity) and perceptual (i.e., tool color, recipient color, number of recipients) attributes. The results for recall of functional associative tool attributes under divided attention are particularly informative considering that motor skill acquisition was unaffected by dividing attention during training. More specifically, these results suggest that motor skill acquisition is not dependent on declarative knowledge related to the tool (e.g., function of the tool).

Tool grasping

As predicted, tool grasping was significantly lower for tools trained under DA relative to FA. This finding is consistent with previous research showing that grasping a tool for the purpose of using it requires declarative memory about the tool's use (Creem & Proffitt, 2001; Roy & Park, 2010). However, grasping accuracy for tools in the FA condition was much lower than expected (only 35 %). This pattern of poor grasping accuracy even in the FA condition suggests that tool grasping has a strong declarative representation that requires extensive repetition.

Limitations and future directions

As noted in the Results, some observations were removed from analysis of completion time measures (i.e., training, use-to-command). Although we had a theoretical rationale for removing this data, specifically to obtain a more "pure" measure of procedural memory, we acknowledge that removal of data may have had an impact on overall findings. Future work could make use of longer time limits of performance trials or provided more training trials to reduce the amount of missing data. In addition, although the current study proposes that specific memory systems play a primary role in mediating different aspects of tool-related knowledge and skills, it is likely that multiple memory systems and cognitive processes are involved in the acquisition of tool-related knowledge and skills. For instance, although the current study focuses on the role of procedural memory in mediating skill learning, other forms of nondeclarative memory (i.e., perceptual, cerebellar) are also likely involved in learning of motor skills.

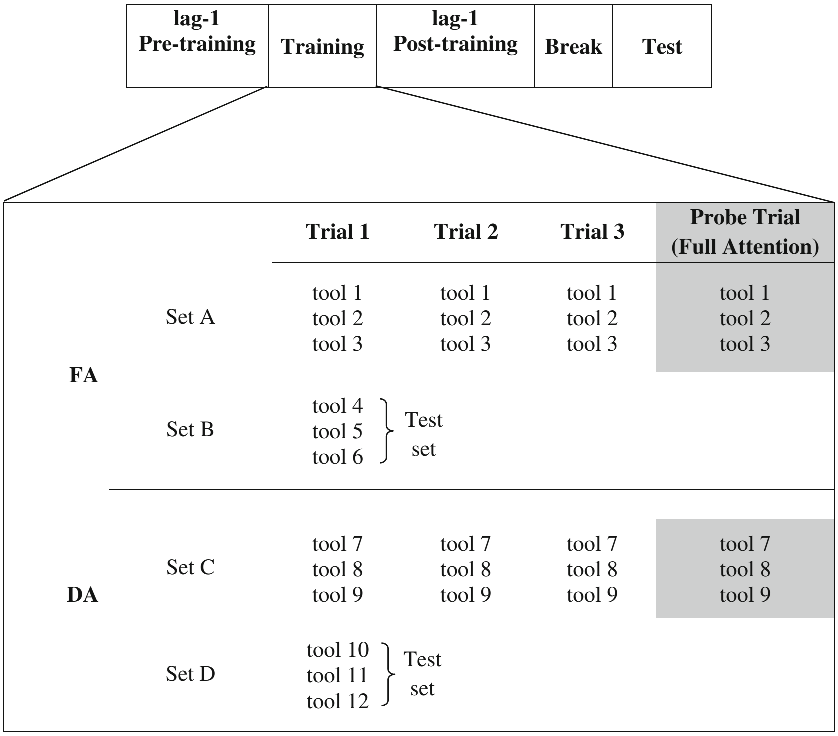
Conclusion

The current study, taken together with previous findings, presents evidence of a dynamic relationship between declarative and procedural memory systems. Results suggest that the contribution of declarative and procedural memory systems varies across different aspects of tool knowledge and skills. Furthermore, although motor skill acquisition and skilled tool use both appear to rely on an interaction of declarative and procedural memory, they rely on different forms of memory interaction (i.e., competitive, cooperative). Thus, the current study provides new insights into the organization of memory within the domain of tool use.

Acknowledgments We would like to express our gratitude to all the participants who graciously took the time to complete this experiment. We would also like to thank Naveen Gnanabakthan for assistance with initial development of novel tool tasks and interrater scoring. This project was funded by an internal grant awarded to Dr. Norman Park.

Appendix

Experimental design



		Trial 1	Trial 2	Trial 3	Probe Trial (Full Attention)
FA	Set A	tool 1 tool 2 tool 3	tool 1 tool 2 tool 3	tool 1 tool 2 tool 3	tool 1 tool 2 tool 3
	Set B	tool 4 tool 5 tool 6 } Test set			
DA	Set C	tool 7 tool 8 tool 9	tool 7 tool 8 tool 9	tool 7 tool 8 tool 9	tool 7 tool 8 tool 9
	Set D	tool 10 tool 11 tool 12 } Test set			

References

Brown, R. M., & Robertson, E. M. (2007). Inducing motor skill improvements with a declarative task. *Nature Neuroscience, 10,* 148–149. doi:10.1038/nn1836

Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology, 17,* 177–184. doi:10.1016/j.conb.2007.03.005

Corkin, S. (1968). Acquisition of motor skill after bilateral medial temporal-lobe excision. *Neurocase, 2*(4), 259f–298f. doi:10.1093/neucas/2.4.259-f

Creem, S. H., & Proffitt, D. R. (2001). Grasping objects by their handles: A necessary interaction between cognition and action. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 218–228. doi:10.1037/0096-1523.27.1.218

Creem-Regehr, S. H., & Lee, J. N. (2005). Neural representations of graspable objects: Are tools special? *Cognitive Brain Research, 22,* 457–469. doi:10.1016/j.cogbrainres.2004.10.006

Dobbs, A. R., & Rule, B. G. (1989). Adult age differences in working memory. *Psychology and Aging, 4,* 500–503. doi:10.1037/0882-7974.4.4.500

Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., … Benali, H. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioural Brain Research*, *199*, 61–75. doi:10.1016/j.bbr.2008.11.012

Eysenck, H. J., & Thompson, W. (1966). The effects of distraction on pursuit rotor learning, performance and reminiscence. *British Journal of Psychology, 57,* 99–106. doi:10.1111/j.2044-8295.1966.tb01009.x

Fernandes, M. A., & Moscovitch, M. (2013). Divided attention and memory. In H. Pashler (Ed.), *Encyclopedia of the mind*. SAGE: Thousand Oaks. doi:10.4135/9781452257044.n98

Foerde, K., Poldrack, R. A., & Knowlton, B. J. (2007). Secondary-task effects on classification learning. *Memory & Cognition, 35,* 864–874. doi:10.3758/bf03193461

Foerde, K., & Shohamy, D. (2011). The role of the basal ganglia in learning and memory: Insight from Parkinson's disease. *Neurobiology of Learning and Memory, 96,* 624–636. doi:10.1016/j.nlm.2011.08.006

Foundas, A. L., Macauley, B. L., Raymer, A. M., & Maher, L. M. (1995). Ecological implications of limb apraxia: Evidence from mealtime behavior. *Journal of the International Neuropsychological Society, 1,* 62–66. doi:10.1017/s1355617700000114

Frensch, P. A., Lin, J., & Buchner, A. (1998). Learning versus behavioral expression of the learned: The effects of a secondary tone-counting task on implicit learning in the serial reaction task. *Psychological Research, 61,* 83–98. doi:10.1007/s004260050015

Frey, S. H. (2007). What puts the how in where? Tool use and the divided visual streams hypothesis. *Cortex, 43,* 368–375. doi:10.1016/s0010-9452(08)70462-3

Gabrieli, J. D., Corkin, S., Mickel, S. F., & Growdon, J. H. (1993). Intact acquisition and long- term retention of mirror-tracing skill in Alzheimer's disease and in global amnesia. *Behavioral Neuroscience, 107,* 899–910. doi:10.1037//0735-7044.107.6.899

Gobel, E. W., Blomeke, K., Zadikoff, C., Simuni, T., Weintraub, S., & Reber, P. J. (2013). Implicit perceptual-motor skill learning in mild cognitive impairment and Parkinson's disease. *Neuropsychology, 27,* 314–321. doi:10.1037/a0032305

Goh, H.-T., Sullivan, K. J., Gordon, J., Wulf, G., & Winstein, C. J. (2012). Dual-task practice enhances motor learning: A preliminary investigation. *Experimental Brain Research, 222,* 201–210. doi:10.1007/s00221-012-3206-5

Gold, D. A., & Park, N. W. (2008). The effects of dividing attention on the encoding and performance of novel naturalistic actions. *Psychological Research, 73,* 336–349. doi:10.1007/s00426-008-0148-4

Goldenberg, G., & Spatt, J. (2009). The neural basis of tool use. *Brain, 132,* 1645–1655. doi:10.1093/brain/awp080

Heilman, K. L. (2002). *Matter of mind*. New York, NY: Oxford University Press. doi:10.1093/acprof:oso/9780195144901.001.0001

Hodges, J. R., Bozeat, S., Lambon Ralph, M. A., Patterson, K., & Spatt, J. (2000). The role of conceptual knowledge in object use. *Evidence from semantic dementia. Brain, 123,* 1913–1925. doi:10.1093/brain/123.9.1913

Iidaka, T., Anderson, N. D., Kapur, S., Cabeza, R., & Craik, F. I. M. (2000). The effect of divided attention on encoding and retrieval in episodic memory revealed by positron emission tomography. *Journal of Cognitive Neuroscience, 12,* 267–280. doi:10.1162/089892900562093

Kantak, S. S., & Winstein, C. J. (2012). Learning–performance distinction and memory processes for motor skills: A focused review and perspective. *Behavioural Brain Research, 228,* 219–231. doi:10.1016/j.bbr.2011.11.028

Knowlton, B. J., Mangels, J. A., & Squire, L. R. (1996). A neostriatal habit learning system in humans. *Science, 273,* 1399–1402. doi:10.1126/science.273.5280.1399

McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why there are complementary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychological Review, 102,* 419–457. doi:10.1037/0033-295x.102.3.419

Moody, T. D., Bookheimer, S. Y., Vanek, Z., & Knowlton, B. J. (2004). An implicit learning task activates medial temporal lobe in patients with Parkinson's disease. *Behavioral Neuroscience, 118,* 438–442. doi:10.1037/0735-7044.118.2.438

Morris, C. D., Bransford, J. D., & Franks, J. J. (1977). Levels of processing versus transfer appropriate processing. *Journal of Verbal Learning and Verbal Behavior, 16*(5), 519–533. doi:10.1016/s0022-5371(77)80016-9

Moscovitch, M., Nadel, L., Winocur, G., Gilboa, A., & Rosenbaum, R. S. (2006). The cognitive neuroscience of remote episodic, semantic and spatial memory. *Current Opinion in Neurobiology, 16,* 179–190. doi:10.1016/j.conb.2006.03.013

Negri, G. A., Lunardelli, A., Gigli, G. L., & Rumiati, R. I. (2007). Degraded semantic knowledge and accurate object use. *Cortex, 43,* 376–388. doi:10.1016/s0010-9452(08)70463-5

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19,* 1–32. doi:10.1016/0010-0285(87)90002-8

Penhune, V. B., & Steele, C. J. (2012). Parallel contributions of cerebellar, striatal and M1 mechanisms to motor sequence learning. *Behavioural Brain Research, 226,* 579–591. doi:10.1111/j.1749-6632.2011.06434.x

Reber, A. S. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious*. Oxford: Oxford University Press. doi:10.1093/acprof:oso/9780195106589.001.0001

Roche, R. A. P., Commins, S., Agnew, F., Cassidy, S., Corapi, K., Leibbrand, S., … O'Mara, S. M. (2007). Concurrent task performance enhances low-level visuomotor learning. *Perception & Psychophysics, 69*, 513–522. doi:10.3758/bf03193908

Roy, S., & Park, N. W. (2010). Dissociating the memory systems mediating complex tool knowledge and skills. *Neuropsychologia, 48,* 3026–3036. doi:10.1016/j.neuropsychologia.2010.06.012

Roy, S., Park, N. W., Roy, E. A., & Almeida, Q. (2015). Interaction of memory systems during acquisition of tool knowledge and skills in Parkinson's disease. *Neuropsychologia, 66,* 55–66. doi:10.1016/j.neuropsychologia.2014.11.005

Shohamy, D., Myers, C. E., Kalanithi, J., & Gluck, M. A. (2008). Basal ganglia and dopamine contributions to probabilistic category learning. *Neuroscience & Biobehavioral Reviews, 32,* 219–236. doi:10.1016/j.neubiorev.2007.07.008

Siegert, R. J., Taylor, K. D., Weatherall, M., & Abernethy, D. A. (2006). Is implicit sequence learning impaired in Parkinson's disease? A meta- analysis. *Neuropsychology, 20,* 490–495. doi:10.1037/0894-4105.20.4.490

Silveri, M. C., & Ciccarelli, N. (2009). Semantic memory in object use. *Neuropsychologia, 47,* 2634–2641. doi:10.1016/j.neuropsychologia.2009.05.013

Song, S., Howard, J. H., & Howard, D. V. (2007). Implicit probabilistic sequence learning is independent of explicit awareness. *Learning & Memory, 14,* 167–176. doi:10.1101/lm.437407

Squire, L. R. (2009). Memory and brain systems: 1969–2009. *Journal of Neuroscience, 29,* 12711–12716. doi:10.1523/jneurosci.3575-09.2009

Warrington, E. K. (1975). The selective impairment of semantic memory. *The Quarterly Journal of Experimental Psychology, 27,* 635–657. doi:10.1080/14640747508400525

Warrington, E. K., & Shallice, T. (1984). Category specific semantic impairments. *Brain, 107,* 829–854. doi:10.1093/brain/107.3.829

Weisberg, J., van Turennout, M., & Martin, A. (2007). A neural system for learning about object function. *Cerebral Cortex, 17,* 513–521. doi:10.1093/cercor/bhj176

Wilkinson, L., Khan, Z., & Jahanshahi, M. (2009). The role of the basal ganglia and its cortical connections in sequence learning: Evidence from implicit and explicit sequence learning in Parkinson's disease. *Neuropsychologia, 47,* 2564–2573. doi:10.1016/j.neuropsychologia.2009.05.003