COGNITIVE PROCESSES THAT SUPPORT ADULT MEMORY FOR NOVEL SEQUENTIAL ACTIONS

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Abstract

Recalling the order of action sequences plays a considerable role in everyday routine functioning, but relatively little is known about the underlying cognitive processes behind the learning of such action sequences. The current study explored the role of prior knowledge in sequence learning, and the relative importance of verbal and motor processing during this learning. Participants viewed a series of action sequences and were either given prior knowledge of the object categories used in the sequences or not and were additionally asked to perform a motor or verbal dual task during learning, or had no dual task. After a delay they were asked to recall the sequence with a novel set of items. Recall for the action sequence was significantly stronger without the presence of a dual task, both with and without prior knowledge. There was also partial evidence that verbal processes may be more heavily involved in learning in comparison to motor processing. These findings indicate that full attention is required for action learning, and that real-world learning of actions may rely most heavily on verbal working memory.

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Cognitive Processes that Support Adult Memory for Novel Sequential Actions

Sequential actions are a standard practice in everyday life. When completing seemingly basic tasks, like making a bed or getting dressed for the day, we are only able to practically complete them by following order. For example, when making a meal and following a recipe, the order and procedure appears obvious to produce the end result. When making the same meal repeatedly, the recipe with instructions is no longer needed, instead it becomes second nature. This is because the order of the sequential actions have been stored in long-term memory. This is possible because of the innate capacity for this behaviour. Understanding order does not just affect the ability to accomplish independent activities, it also affects the ability to function in various social environments. Understanding order, and having the capacity to remember it, can facilitate anticipation of future events, aid in the ability to relay stories, learn sports plays, and generally communicate conversationally. In any case, order is foundational in the role of the human experience. For that reason, it is critical to understand how humans exercise their capacity to remember such actions.

Working memory functions as a temporary buffer for processing information going into, and coming out of, long-term memory. Here, information can be briefly stored, manipulated, and eventually encoded (Hasselmo & Stern, 2006). A highly accepted model of working memory follows a three sub-component structure which includes the visuospatial sketchpad, the phonological loop, and the episodic buffer (Baddeley, 2000). These components are known as slave systems, which are controlled by the overarching central executive. The central executive is in charge of information processing, directing attention, memory retrieval, and delegates work via the previously mentioned slave systems. In this process, information is collected, interpreted, and sent to the appropriate system. This model has enriched our understanding of how information is processed between short-term and long-term memory (Baddeley, 2000 and Baddeley & Hitch, 1974).

There are thought to be different functions and carrying capacities of the working memory's slave systems, as they relate to the type of stimuli that are encountered. For example, Gmeindl et al. (2011) show an important difference between spatial working memory and verbal working memory in terms of the ability to bind serial order to the representation of a stimulus sequence. They proposed that stimuli presented auditorily, as opposed to visually, may be encoded with a greater level of temporal precision. This, in turn, leads to an improved feature distinctiveness of an auditory stimulus in memory. Gmeindl et al. also demonstrated that encoding spatial representations requires significantly greater working memory resources than verbal representations. When the capacity for such representations begins to reach its limit, the binding of serial order is abandoned (but storage of the individual items is still maintained). As such, they theorized that standardized memory testing may be underestimating the effective capacity of spatial working memory. Overall, this research shows differences between the kind of stimulus and the availability of an ordered representation in working memory.

Most studies that examine the relationship between incoming and outgoing information from our memory utilize verbal stimuli, such as lists of words or numbers (Hurlstone et al, 2014). There is minimal research on visuospatial memory, and even less research on memory for sequential action (Loucks et al, 2019). For example, Agam et al. (2005, 2007) conducted studies on imitating novel 2-dimensional motion sequences. In this research, participants were to remember and imitate a series of spatial paths that were demonstrated with a dot on a computer screen. While this approach can inform our understanding of motor sequences through imitation, the actions performed in the study were very simple. In the real world, the sequential actions that people perform, sometimes for functional or even critical reasons, require the learning of more complex, and sometimes deviating, sequences (e.g., Loucks et al., 2020). Similarly, the research on tactile memory and the Hebbian learning effect, where a simple, identical sequence is repeated over and over again in learning (Johnson et al, 2016), shares little about learning sequences in the real world.

Some sequences people experience can be unpredictable, to a degree, in that they contain variable characteristics across different events (e.g., differences in the items used in each instance). As such, a relatively simple script - mental categorical function that produces familiarity and predictability - cannot be used when encountering such stimuli (Schank and Abelson, 1977). When sequences deviate significantly, people may not be able to continue to function appropriately. For example, Loucks and Price (2019) investigated the effects of variable item and temporal information in young children's memory for action. They found that encountering deviant temporal order during learning can be highly deleterious to recall of temporal information in action. They also demonstrated that the encoding of temporal information follows a processing hierarchy, such that encoding of this information is the most efficient if the observer's attention is not focused on the specific items in the sequence (e.g., apple, banana, grapes), but can instead be focused on the general categories that the items used in the sequence belonged to (e.g., fruit). Both results highlighted that memory for order in action is the least prioritized information, and as such requires significant resources to encode.

Note that the above research was conducted on young children. However, it is likely the effects that were demonstrated were not properties of the immature cognitive system, but would persist into adulthood as aspects of general human memory. Loucks et al. (2020) explored this idea directly, by investigating the processing hierarchy and the effect of temporal deviation on adults' ability to learn temporal order in action. They hypothesized the presence of deviant order would inhibit participants' ability to recall the action sequences, especially when the items in the sequence were harder to categorize. Their study involved the use of easy-item and difficult-item sets for the action sequences. The easy-item set included items which appeared easily identifiable (fruit and vehicles), while the difficult-item set included objects from overarching categories which are harder to identify (metal items and small items). Participants watched four videos of a person performing an action sequence with either the easy or difficult sets, and either saw consistent order across all videos, or consistent order on three and a deviant order on one. After watching these sequences, and after completing several tasks across a 20-minute span, they were asked to repeat the action sequence they had viewed in the videos. The results showed that adults, like children, have fragile temporal encoding: there was little effect of the deviant order in the easy item condition on the recall of their standard order, but in the difficult item condition the same deviant order greatly inhibited the recall of the standard order. This finding further supports the theory of the processing hierarchy by showing that imposing such demanding semantic properties on the observer generates downstream effects on their memory for temporal order. Note that participants were able to recall the individual items, even when their recall for the action sequence using said items was greatly inhibited.

In Loucks and Price (2019) and Loucks et al. (2020), the hypothesis is that when items in the sequence are less identifiable, a greater draw is enacted on working memory resources, and this produces downstream effects on sequential recall. Theoretically, then, if participants were to be made aware of the semantic properties prior to learning the sequence, then resources would be spared. Therefore, using difficult item categories should not impair recall as significantly if the observer has prior knowledge of their presence. Testing the effect of knowledge directly in this manner would be a means of evaluating this hypothesis.

There is additional potential benefit to investigating more fully the cognitive resources that are utilized when individuals learn such complex sequences of action. One possibility, given these semantic effects, is that learning the sequence utilizes the phonological loop (i.e., the observer subvocalizes the actions that are being executed as they watch it). Another possibility follows the idea that they utilize their motor system, and "mirror" the actions as they observe them (Cattaneo and Rizzolatti, 2009). If the language system or the motor system were being utilized for a different purpose while the observer was learning the sequence, then it could be demonstrated which resource is more typically needed during sequential action learning.

The present study aims to determine the cognitive processes supporting adult memory for novel sequential actions, by examining the role of verbal and motor inhibitions on the ability for adults to recall novel motor sequential actions, while also examining the role of item category knowledge on processing and recall. The task will require adults to watch a series of sequential action videos using difficult item categories. Across the four videos, the actions and item categories remain the same, however, the specific objects will be different in each video. Participants will either be in the knowledge condition, where they will be made aware of the categories ahead of time, or the naïve condition, where they will be unaware of this information. Further, participants will observe the videos while either engaging in a motor dual task (i.e., tapping a finger pattern with both hands to the beat of a metronome), or a verbal dual task (i.e., shadowing spoken words), or no dual task at all. I hypothesize that knowledge will mitigate the effect of item difficulty, and thus I predict that recall will be higher in the knowledge condition over the naïve condition. Further, I hypothesize that the inhibition of both verbal and motor means of memory will result in a poorer recall for the action sequence, but given that no previous research has used such conditions, I am uncertain which task will interfere more.

Methods

Participants

Participants in this study were undergraduate students at the University of Regina. They were recruited through the University of Regina's Sona System Psychology Participant Pool, and received partial course credit for their participation. The 140 participants (43 male) included 59 White (42.1%), 24 South Asian (17.1%), 25 Black (17.9%), 12 Southeast Asian (8.6%), 8 Mixed race (5.7%), 5 East Asian (3.6%), 4 Middle Eastern (2.9%), 2 who preferred not to answer (1.4%), and 1 North African (0.7%) individuals. One participant was later removed from analysis due to not being recorded. A power analysis for a 2 x 3 factorial ANOVA with an alpha = .05 and power = .80 indicated that a sample size of 23 in each condition (*N* =138 total) would be sufficient for detecting a medium effect size (*f* = .27) in the interaction term. Random assignment divided the sample equally among the 6 conditions, with 23 participants per condition, except the knowledge verbal condition which had 24 (an extra participant was due to scheduling). This research has been approved by the University of Regina Research Ethics Board.

Stimuli

The items used for the Replication Phase were from the same categories as those used in the video sequence and were arranged on a small wooden table. Specifically, the four objects are: 1) a grey mug, 2) a red pen, 3) a space-themed paper cupcake liner, and 4) a black plastic clip. Figure 1 displays the items in the arrangement that they appeared to participants.

Figure 1

Stimulus arrangement that was presented in the Replication Phase.

As in Loucks et al. (2020), a video involving four action sequences was created for use in the Exposure Phase. In each sequence, an actor is seated in front of four objects: 1) a mug, 2) a pen, 3) a paper item, and 4) a small item (smaller than all of the other items). The specific form of each object varies in each sequence (e.g., there will be four unique mugs).

The sequence will be as follows: 1) tap the pen on the paper item 3 times, 2) touch the paper item and the small item together, meeting in the middle, 3) thread the pen through the handle of the mug, 4) circle the mug around the small item twice. All items return to their original places after use in an action. Each sequence is approximately 10 seconds long. The four sequences appear in a fixed order and are separated by a 5 second blank screen between sequences. There is no sound in the video, with the exception of the audio track used in the verbal condition.

Memory Tasks

In between the Exposure and Replication Phases, participants engaged in three memory tasks.

Digit Span

The researcher read aloud numbers at a rate of one per second, starting with 2 digits (e.g., 7, 2), to the participants. Participants were instructed to repeat the numbers back to the researcher in the same order they were said to them. There were two number sets for each digit span. If both sets of the span were incorrect, the task ended. Participants could go up to a maximum of 10 digits.

Backward Digit Span

This task followed the same format of the above digit span, except the participants were now instructed to repeat the given numbers in the reverse order (e.g., the researcher says 8, 5, the participant repeats back 5, 8). Participants can go up to a maximum of 8 digits.

Corsi Block-Tapping Test

The researcher set out a board of wooden blocks, which were blank on the participant's side and labelled with numbers on the researcher's side. The researcher tapped the top of the blocks in a sequence at a rate of one per second, and participants were instructed to touch the blocks in the same sequence. Task structure was the same as the digit tasks otherwise. Participants could go up to a maximum sequence of 9 touches.

Design & Procedure

Participants visited the lab on one occasion for approximately 30 minutes. I use a 2 (knowledge vs. naïve) x 3 (motor vs. verbal vs. no dual task) between-subject design. There are thus 6 conditions: 1) Knowledge Verbal, 2) Naïve Verbal, 3) Knowledge Motor, 4) Naïve Motor, 5) Knowledge No Dual, and 6) Naïve No Dual.

Introduction and Exposure Phase

Upon arriving at the lab and providing consent, participants first reported on their gender and race/ethnicity through a Qualtrics survey on an iPad. Following this, the researcher led the participant to a smaller room within the lab, where participants were seated in front of a computer. The introduction to the Exposure Phase varied based on the participants' assigned condition. All conditions began with the general instruction: "For the study today, there are four parts. In the first part, you will be watching some videos on the computer here. In the videos a person will be performing a sequence of actions with some objects. Please watch the videos carefully, as I may ask you questions about them later." Following this initial preamble, condition instructions varied.

Knowledge Conditions. "The objects will always be the same across the videos. There will always be a mug, a pen, a thing made of paper, and a small thing. There will just be different versions of these in each video. So, a mug, a pen, a thing made of paper, and a small thing."

Naïve conditions. There was no additional information provided about the nature of the videos.

Verb Conditions. "While you are watching the videos, you will also have to shadow words that someone else is speaking. Shadowing is when you speak aloud the words you are hearing right as they are being spoken. So when you hear a word, you immediately say it, and you are listening and speaking at the same time. We will start with some practice”. This was followed by a blank video in which words are played over to practice the shadowing task in isolation. “Okay, now I will start the videos, and you start shadowing right when it starts.”

Motor Conditions. “While you are watching the videos, you will also have to perform a finger tapping action with both hands to the beat of a metronome. So first, I will show you how to do the pattern. Like this: (researcher then demonstrated the action). Now you try for a bit.” The participant then had an opportunity to practice the task in isolation. “Okay, you keep tapping and I will start the videos.” The metronome was played over the researcher’s mobile phone and was set at 90 bpm.

No Dual Task. In these conditions there was no additional instruction about performing a dual task.

Memory Tasks

Following the Exposure Phase, participants were brought back to the initial room in the lab that they started in, to which they were directed to sit across from the researcher at a table. Here participants were presented with the standardized memory tasks, in a fixed order of digit span, backward digit span, and Corsi block-tapping.

Puzzle Task

Upon completing the memory tasks, the researcher presented a 60-piece puzzle. Participants were given approximately 10 minutes to complete the puzzle. While participants worked to complete the puzzle, the researcher stepped away to set up the stimuli for the Replication Phase on a table in the room where the Exposure Phase occurred.

In the event the participant finished the puzzle before the 10-minute mark, the researcher attempted to stall to 10 minutes by conversing with the participant. If the participant was not done shortly after the 10-minute mark, the researcher instructed them to leave the puzzle on the table.

Test Phase

After the completion of the puzzle task, participants were guided back to the room from the Exposure Phase. They were seated at a table in front of the items already displayed (see Figure 1). The researcher began recording the participant, and instructed them by saying: "Okay, remember those videos you watched before? Well, I have got some items here, and I want you to do what the person in the video did, with these things here, from the first part. Even if it is hard, just try your best to remember." Participants had an unlimited amount of time to recall the sequence.

Following the Replication Phase the participants were debriefed.

Procedure Duration

The study is approximately broken down as described: A) Consent/Demographics – 1 minute, B) Introduction and Exposure Phase – 1-3 minutes, C) Memory Tasks – 15 minutes, D) Puzzle Task– 10 minutes, E) Replication Phase – 1 minute.

Scoring

Coding measures were adapted from Loucks et al (2020). Target sub-actions (actions 1, 2, 3, and 4) were scored as follows: a score of 1 was given when the target action was exhibited (minor deviations acceptable – e.g., tapping less than 3 times), a score of 0.5 was given for actions that either involve the correct two target objects but the action does not fulfill target criteria (e.g., putting the pen inside the mug would count as 0.5 for action 3), or was the correct target action but with one or more incorrect objects (e.g., circling the small object with the pen would count as action 4), and a score of 0 was given if nothing resembling a target action was performed. Individual sub-action scores were then totaled into a sub-action score, which could thus range from 0 to 4.

Partial order was scored as follows: a score of 1 was granted when only two target actions are performed in sequence, a score of 2 was granted when only a triplet of target actions were performed in sequence, and a score of 3 was granted when all four target actions were performed in sequence. A score of 0 was granted when no consecutive actions were completed in order. Partial order scores could thus range from 0 to 3.

Coding was done in full by a research assistant blind to the hypotheses, and 20% of the sample was also coded by the primary researcher for the purposes of inter-rater reliability. Reliability was high: 89% and 93% agreement on sub-action and partial order scores, respectively.

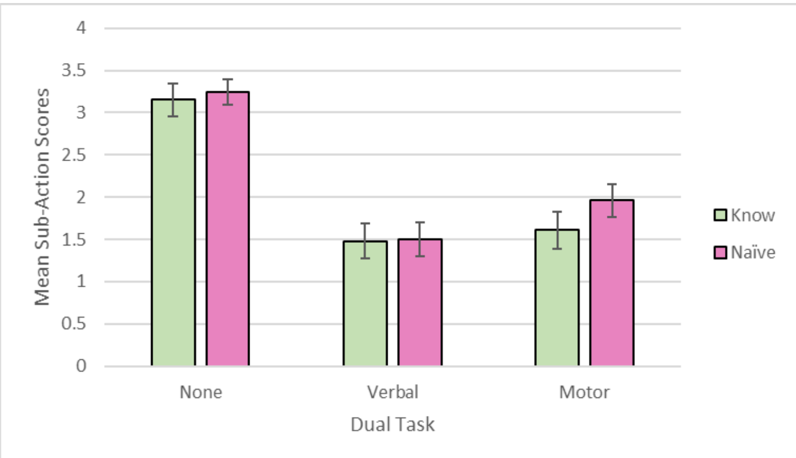
Results

Sub-action Scores

Mean sub-action scores for each condition can be found in Figure 2. A 2 (knowledge vs. naïve) x 3 (motor vs. verbal vs. no dual task) Factorial ANOVA on sub-action scores revealed a main effect on dual scores, $F(2,\text{-}138) = 43.27$, $p = < .001$, partial eta squared = .394. No other main effects or interactions were significant, both $F(1,\text{-}138) < 0.9$, $p > 0.34$. As is clear in the figure, participants with no dual task performed better than those with a dual task, with no observable differences between scores in the verbal and motor conditions.

Figure 2

Mean Sub-Action Scores

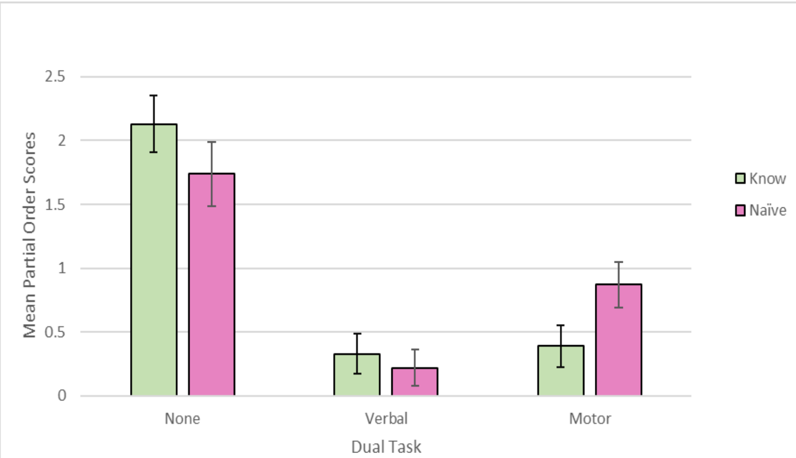


Partial Order Scores

Mean partial order scores can be found in Figure 3. A 2 (knowledge vs. naïve) x 3 (motor vs. verbal vs. no dual task) Factorial ANOVA revealed a significant main effect of dual task, $F(2,138) = 35.34$, $p < .001$), partial eta squared = .39, and a marginal interaction between knowledge and dual task, $F(1,138) = 2.74$, $p = .068$), partial eta squared = .04,. The effect of the dual task was the same as with sub-actions. As a result of the marginal interaction, a follow up independent samples *t*-test was conducted comparing performance on the verbal and motor dual tasks between knowledge conditions. In the knowledge condition the means are practically identical, $t(45) = 0.26$, $p > .80$, while in the naïve condition, partial order scores were significantly higher in the motor condition compared to the verbal condition, $t(44) = 2.85$, $p = .007$, Cohen's d= 0.84.

Figure 3

Mean Partial Order Scores



Discussion

Recalling the order of action sequences plays a considerable role in everyday routine functioning. To date, most research on memory has utilized verbal stimuli, as opposed to the use of visuospatial and action stimuli. Thus, relatively little is known about the underlying cognitive processes behind the learning of action sequences, and what is known may not translate to real-world application (Loucks et al., 2019). I hypothesized that prior knowledge of the object categories would assist in learning an action sequence, and thus predicted that recall for the action sequence will be higher in the knowledge condition over the naïve condition. Further, I hypothesized that the inhibition of both verbal and motor means of memory will result in a poorer recall of the action sequence, and thus both dual task conditions would have lower recall than the no dual task condition. Due to the limit of prior research, I held no hypothesis regarding which dual task would interfere with recall to a greater degree.

The current study revealed significantly higher recall for both sub-action and partial-order scores when the participants did not have a dual task compared to when a dual task generally was present. This is in line with the second hypothesis. The current work also provided some evidence to support the idea that verbal processes are more important to learning novel actions than motor processes. However, contrary to the first hypotheses, there was no main effect of knowledge on recall. In none of the knowledge conditions was recall higher than the naïve conditions. Interestingly, the small difference in dual task previously described was that the recall of the temporal order was higher in the naïve motor dual task condition than the knowledgeable motor dual task condition. We will discuss each of these effects in turn.

First, the poorer recall in the presence of inhibitions on both motor and verbal processing systems support the hypothesis, as well as the theory, that the acquisition of novel sequential actions is an attentionally demanding task, even for adults. This large main effect in the present data is suggestive of a decrease in the functioning of working memory when its resources are required to be divided. Regardless of what kind of dual task was being undertaken, one's ability to remember the sequence was greatly hindered, even when having prior knowledge of the object's categories was available as a potential cognitive savings.

On the one hand, any kind of dual task interfered with learning. This is consistent with the idea that full attention is required to optimal learning. It is also consistent with the idea that both verbal and motor processing systems are utilized in learning novel sequential actions, to an equal extent, and missing one or the other impairs learning. However, there was an unexpected finding that may indicate that verbal processing is more critical than motor processing. Specifically, only in the naïve condition, the motor dual task partial order scores were higher than the verbal dual task partial order scores. This might mean that verbal cognitive processes aid in learning to a greater extent than motor processes. However, no similar effect was observed in the knowledge condition, which makes it more difficult to interpret.

The lack of a knowledge effect on learning more generally was also unexpected, and contrary to the hypothesis. While there is no research in the current body of literature examining a rationale for this finding, I speculate that it may be due to participants focusing on the items themselves, which therefore worked as a distraction from learning the action sequence itself during encoding. By explicitly pointing the participants to the item categories, they may have prioritized encoding of the items instead of the sequence. However, more research is needed before a firm conclusion can be drawn on this point.

The novelty of the current study adds to the limited body of research on how people learn new action sequences. By examining memory for novel action sequences, this study provides critical insight into the worldly applications of working memory in motor sequences. This, in turn, allows future researchers to consider memory in more complex scenarios that align with the demands of learning new action sequences in the real world. Ultimately, we can conclude that full attention is necessary for action learning and that verbal working memory may be more heavily relied upon in cognitive functioning for memory and recall.

A potential limitation to the study worth noting is the level of difficulty for the item categories used. The current study utilized ‘difficult to categorize' items in an attempt to understand the demands of real-world application. However, future research may benefit from testing the cognitive processes in learning actions with varying levels of item difficulty, including easier ones. I predict that the easier to categorize items will not have a significant impact on the result, consistent with findings by Loucks et al. (2020). However, more clarity on the nature of verbal vs. motor processing in learning may be found by using easier categories.

It is also important to note that this study did not control for age or demographic considerations. Future research on this area may consider narrowing in on more specific age categories, demographics, etc., that were recorded, but not controlled for, in this study. The current study examined memory in undergraduate students, and I expect the results would apply universally. However, further research within different cultures, ages, backgrounds, etc., is necessary before the conclusions can be properly generalized. The current study does not examine any effects of specific experience that may assist in the action sequence recall. For example, people who play musical instruments may be better tailored to manipulate their hand movements while paying directed attention to the music sheets, and the actions of those around them. This practiced manipulation could in turn give them an unaccounted for advantage in their processing and recall. Lastly, future research is encouraged to consider the role of varying cognitive experiences and potential hindrances/advantages in order to diversify the findings of the current research.

Future research may additionally examine the potential hindrance of knowledge in the action sequence recall in the presence of a dual task. While I suggest it may be the result of an unintentional focus misdirect, it would be wise to probe this effect further. More research on adults' memory generally is also encouraged to add to the limited body of literature in this domain.

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