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Memory for temporal order in novel sequential action

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ABSTRACT
Order is critical for many daily activities. Developmental research has shown that memory for order in action is the least prioritised in a processing hierarchy, and is sensitive to deviant input. The current research investigated these aspects of sequence learning are also present in adults. Participants learned a novel sequence across several exemplars with either easy- or difficult-to-categorize items, which either did or did not involve a deviant order on one exemplar, and were later asked to recall the sequence. Memory for individual sub-actions and order was stronger in the easy conditions, and the deviant order significantly deteriorated ordered recall in the difficult condition only. These findings support the theorised processing hierarchy, with the presence of a deviant order having a larger effect on memory when the load at the earlier item stage is increased. These results have implications for theories of working memory and learning in real-world contexts.

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Memory for temporal order in novel sequential action

The ability to learn order in sequential action is critical in many aspects of human life. When getting dressed in the morning, the order in which clothes are applied matters – putting your socks over your shoes would not be functional. Order is important in social situations as well, such as anticipating upcoming events in a standard coffee shop or restaurant experience (Schank & Abelson, 1977), learning a choreographed dance sequence, or learning a secret team handshake. In these latter cases the order is arbitrary, but must be replicated identically nonetheless. Thus, to be functioning members of society we must learn and remember the temporal order of actions in a wide variety of contexts.

Working memory enables individuals to temporarily store, manipulate, and eventually encode information in long-term memory, and allows for binding serial order to incoming stimulus representations (Baddeley, 2000; Baddeley & Hitch, 1974). The visuospatial sketchpad, the phonological loop, and the episodic buffer – the slave systems controlled by the central executive – have the ability to represent the temporal order of events in highly similar ways (Hurlstone et al., 2014). Research on localisation of function has revealed a dissociation in the brain regions used for temporal versus spatial recall (Ekstrom & Bookheimer, 2007). But while some evidence points to temporal order being encoded and recalled using domain-general systems across memory tasks (Cortis et al., 2015; Guérard & Tremblay, 2008; Surprenant & Neath, 2009), there is also evidence that suggests order is represented using domain-specific mechanisms across tasks (Gmeindl et al., 2011; Hurlstone, 2018; Hurlstone & Hitch, 2018).

Debates about process aside, most of what is known about memory for order comes from research using verbal stimuli, with relatively less on visuospatial stimuli (Hurlstone et al., 2014), and very little on sequential action. Agam and colleagues (Agam et al., 2005, 2007) investigated imitative recall of novel spatial sequences. However, the actions in that research that served as the to-be-remembered items were quite simple (touches on a 2-dimensional surface) relative to what people must learn in the real world, where the items

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themselves may be novel, in addition to the order (e.g. learning a new recipe or game).

Although some sequential events occur identically in each new instance, a great many sequences instead have variable characteristics – specifics that change from instance to instance. This is of course the purpose of possessing a script, which abstracts across variable instances in a predictable manner. But how do we handle information that deviates significantly from what has been previously encountered? Farrar and Goodman (1992) investigated this issue with 4- and 7-year-olds. Children participated in visits to the lab, where they played various games/activities. They either participated in 1 or 3 standard (unchanging) visits followed by one deviant visit (2-visit and 4-visit conditions). In the deviant visit there were three distinct changes: two activities were swapped in order, one used categorically different props, and one was a completely new activity. Two control groups also participated in either one standard or one deviant visit, to test for baseline recall ability. Memory for the deviant visit was poor in the 4-visit condition, and relatively better in the 2-visit condition. But memory for both the standard and deviant visits was worse in the 2-visit condition compared to the control groups. Together, these findings indicate that when a deviant is present, more experience with a standard event shields memory for the details of that standard, but also reduces memory for deviant information.

Though Farrar and Goodman's (1992) study provides evidence that the presence of deviant information can in some cases disrupt the ability to recall details from both standard and deviant events, their findings cannot tell us what types of deviation cause this disruption. Because there were three types of deviation present simultaneously, it is unclear which ones were the source of disruption.

Connolly et al. (2016) recently investigated children's recall for a repeated event when there was only one type of deviant present. Participants viewed magic shows on four different days, with the same general script but with variable details. On the fourth day, the actor wore a large bowtie and specifically named the particular magic show. At the end of this final show (the target instance), participants in the deviation group witnessed a deviation from the general event in the form of a completely novel event. Results showed that when the deviant was present, children's recall of this target instance increased, and that recall for all instances was increased after experiencing a deviation under some conditions (Exp. 3). Connolly et al. suggest that the presence of deviant details in a repeated event elicits rehearsal of all previously seen variable details, and therefore helps consolidate memory for the standard event. The introduction of deviant items or actions may highlight the commonalities in previous instances.

While the results of Connolly et al. (2016) indicate that deviation details may in some cases aid recall, recent research has found that deviance in order actually hinders memory. Loucks and Price (2019) recently investigated this issue in children aged 4- to 8-years-old. Children viewed two different action sequences on one day, each across four instances, and were then asked to perform the action sequences with new items that had not previously been seen on a following day. One instance in one of the sequences was deviant: the four sub-actions in the sequence were identical, but two of the actions switched places in the order (e.g. for a standard sequence of A, B, C, D, the deviant sequence was A, D, C, B). The deviant occurred either in the second or the fourth instance. Children had poorer recall for order the next day when they viewed a deviant instance, even though the majority of observed sequences were in the standard order. This disruption occurred even when the deviant happened in the fourth instance.

In the same study, Loucks and Price (2019) also tested a hypothesis that memory for order is the least prioritised information in a hierarchy of processing steps. They hypothesised that when observing a sequence, one must first process the items involved before processing the sub-actions enacted with those items, before processing the order in which those sub-actions are executed. They investigated whether the ease of item categorisation affects the learning of temporal order in action: how easy it is to sort variable items into an overarching category. They found that sequences with easy-to-categorise items (animals and fruit) led to better recall of the temporal order in comparison to difficult-to-categorise items (green items and small items). Furthermore, there was an interaction between item difficulty and the presence of a deviant order – only for the older children – where the deviant significantly disrupted order recall in the difficult condition but not in the easy condition. These results support the theorised processing hierarchy, where temporal order is the least prioritised information, in that it must follow item and sub-action identification.

In sum, there is still relatively little known about how people learn novel, complex action sequences. Though Loucks and Price (2019) found that temporal information in action is highly sensitive to deviant input, and that encoding of temporal information is only possible if attention is not lingering on the items or sub-actions involved in the sequence, these properties of sequence learning were demonstrated only in children. There are many differences between children's and adults' memory abilities (Gathercole et al., 2004), and the one we consider most strongly here is processing speed. If temporal sensitivity and the processing hierarchy are only relevant at younger developmental stages, when processing speed is considerably slower, then they should not be observed in adults tested under similar conditions. However, if these are fundamental properties of action learning in the human cognitive system, then they should also be present in adults.

The current research thus investigated the effect of order deviance on adults' ability to learn temporal order and investigated the applicability of the theorised processing hierarchy to adults' learning of action sequences. Despite the noted differences in children's and adults' general memory, our hypotheses are consistent with what was observed in children (Loucks & Price, 2019), given our anticipation that the hierarchy would not be qualitatively different across development. We hypothesised that the use of easily categorised items would facilitate recall of the action sequence even when the sub-actions and order are identical between item conditions. We also hypothesised that the presence of a deviant order would hinder recall of the action sequence, but that the effect would be greater for sequences that involve more difficult to categorise items.

Method

Participants

Participants were 128 University of Regina undergraduate students (35 male) who received partial course credit for their participation in the experiment. A power analysis with $\alpha = 0.05$ and power $= .80$ indicated that medium effect sizes ($f = .25$) could be detected with an $N = 128$. This research was approved by the University of Regina Research Ethics Board (file #113R1213).

Stimuli

Stimuli included 10 different sets of items used in action sequences: 4 sets for the easy-item condition, 4 for the difficult-item condition, and 2 sets for each condition that were used in the generalisation trial during the test phase. In the easy-item condition, each set contained two variable items which were relatively easily identified as being members of an overarching category (toy vehicles and fruits), while the two variable items in the difficult-item condition were more difficult in this respect (metal items and small items – smaller than the metal items). The variable items in each set were paired with a coloured wooden stick and a coloured wooden block, which varied only in shape and colour across sets. A full list of items used in the action sets can be found in Table 1.

Action sequences were video recorded for each of the 8 sets used in the exposure phase. These action sequences were presented by a male actor on a white foam board, and were approximately 20 s in length. An example of an easy-item and difficult-item set can be seen in Figure 1. The standard action sequences were: (A) stamp block with fruit/small; (B) tap vehicle/metal three times with stick; (C) touch bottom of fruit/small to bottom of vehicle/metal over the centre of the board; (D) trace circle around block with stick. The action sequence for each item set was also filmed in a deviant order that was presented to participants in the deviant conditions. The four sub-actions in the sequence were identical but were performed in a different order: instead of A, B, C, D, they were ordered A, D, C, B. After completion of both the standard and deviant action sequence, each item was back in its starting position, so no spatial transformation occurred within each video. Across the four action videos in both the easy and difficult

Table 1. Items used in each action sequence set.

Condition	Variable Item 1 Toy vehicles	Variable Item 2 Toy fruit
Easy items	Car Bus Jet ski Airplane Gen: Tractor	Grapes Strawberry Pomegranate Lemon Gen: Watermelon
Difficult items	**Metal items** Candle holder Nail Decorative pear Number "6" (address) Gen: Gravy boat	**Small items** Toy space shuttle Match Marble Toy broom Gen: Plastic container

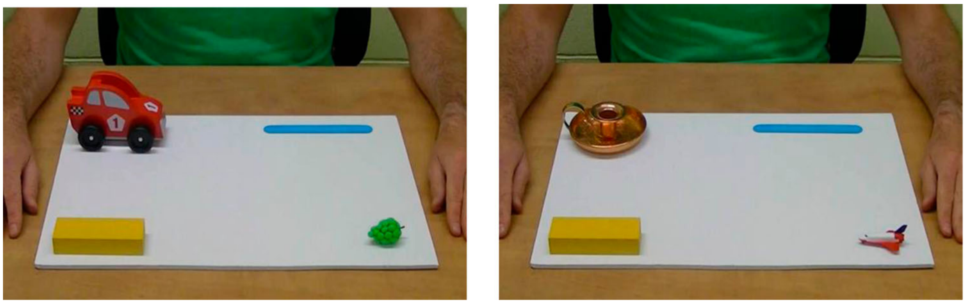

Figure 1. An example easy item (left) and difficult item (right) set.

conditions, the position of items on the board was rotated 90 degrees with each new set of items, to prevent participants from recalling the order based on spatial location.

In addition to the variable items used in the sequences, each variable item had a perceptually similar distractor. Photos of the variable items and their distractors were taken to be used in the item recognition task. Example pairs can be seen in Figure 2.

Design

Participants visited the lab on one occasion for approximately 45 min. We used a 2 (easy vs. difficult items) × 2 (standard vs. deviant presentation) between-subjects design. An additional between-subjects counterbalancing variable was sequence presentation order (two possible orders for which sequence was presented first).

Procedure

After providing informed consent, participants were randomly assigned to one of the four conditions. In the initial exposure phase four action sequence videos were presented on a laptop computer using E-Prime 2.0 software (Psychology Software Tools, Inc., 2016), with unrelated 1-minute animal nature videos presented after each sequence video.[1] In the deviant conditions, the deviant order sequence was always presented second. Participants were told to pay close attention to the videos.

After the exposure phase, participants engaged in two distractor tasks, used to create a 30-minute delay between exposure and test. The first distractor was an unrelated image memory task, which took approximately 12 min. Following this, they were directed to complete as many word searches as they could in approximately 18 min (provided on paper).

In the subsequent test phase, participants were seated at a new table and presented with a generalisation set on a white foam board (either the easy or difficult set, according to condition), and asked to perform the sequence that they had seen in the videos.[2] Following the sequence recall task, participants completed the item recognition task. Participants were provided with eight images at a time – four variable items that were used in the action sequences, along with their distractor pairs – and asked to identify which four items they had seen in the videos. This was completed first for vehicles/metal items then for fruit/small items. Both tasks were video-recorded.

Scoring

Scoring of both tasks was performed from video by one scorer blind to condition. Three scores were scored from the two tasks: a sub-action score, a partial order score, and an item recognition score. A second scorer, blind to condition, coded 32 videos (25%) for reliability. Agreement was 100%.

The sub-action score reflected how many sub-actions the participant correctly recalled. One point was awarded for each, without regard for the order they were performed in. Minor deviations in sub-actions (e.g. tapping more or fewer times) were coded as partially correct and scored as 0.5, but major deviations were scored as 0 (e.g. using

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[1] The animal nature videos were used to break up the presentation of the videos, and also served as a general memory check at the end of the experiment. All participants remembered seeing each of the animal videos.

[2] A small number of participants ($n = 4$) in the deviant conditions at this point asked questions about "Which sequence" (e.g., "Which one? Cause there were like 3 of them"). They were told to perform "the one you saw in the videos", without acknowledging that there were different sequences.

Figure 2. Example variable and distractor items used in the item recognition task.

Table 2. Means (standard deviations) across item difficulty and deviant conditions.

Conditions		Item	Sub-action	Partial order
Easy	Standard	5.50 (1.88)	2.83 (1.08)	1.56 (1.22)
	Deviant	5.91 (1.89)	2.84 (0.92)	1.19 (1.12)
Difficult	Standard	5.63 (1.60)	2.36 (1.22)	1.09 (1.23)
	Deviant	6.09 (1.94)	2.28 (1.06)	0.31 (0.47)

wrong items). Sub-action scores thus ranged from 0 to 4.

The partial order score reflected memory for the temporal order of the sub-actions. Participants were given a 0 if no sub-actions were properly ordered, a 1 if a pair were in order, a 2 if three were in order, and a 3 if they ordered all four correctly. This score could range from 0 to 3.

The item recognition score reflected how many of the variable items were correctly identified. Participants received one point for each correctly selected item, provided they did not also select the item's distractor. This score could thus range from 0 to 8.

Results

Item recognition

Mean item recognition scores are presented in Table 2. A 2 (item difficulty: easy vs. difficult) × 2 (deviancy: standard vs. deviant) factorial ANOVA revealed no significant main effects of item difficulty, $F(1, 124) = 0.23$, $p = .63$, or of deviancy, $F(1, 124) = 1.82$, $p = .18$. The interaction was also not significant, $F(1, 124) = 0.009$, $p = .92$. Thus, item memory was equivalent across conditions, despite the categorisation manipulation.

Sub-action scores

See Table 2 for mean sub-action scores across conditions. A 2 (item difficulty) × 2 (deviancy) factorial ANOVA revealed a significant main effect of item, $F(1, 124) = 7.34$, $p = .008$, $\eta_p^2 = .06$, with more actions remembered in the easy than difficult condition. There was no effect for deviancy, $F(1, 124) = 0.03$, $p = .87$, and no interaction, $F(1, 124) = 0.06$, $p = .80$.

Partial order scores

Figure 3 displays partial order scores by condition and deviancy (see Table 2 for descriptives). A 2 (item difficulty) × 2 (deviancy) factorial ANOVA revealed a significant main effect of item, $F(1, 124) = 12.95$, $p < .001$, $\eta_p^2 = .10$, with better memory in the easy condition, as well as a significant main effect of deviancy, $F(1, 124) = 9.59$, $p < .002$, $\eta_p^2 = .07$, with better memory in the standard condition. However, there was not a statistically significant interaction between condition and deviancy, $F(1, 124) = 1.18$, $p = .28$.

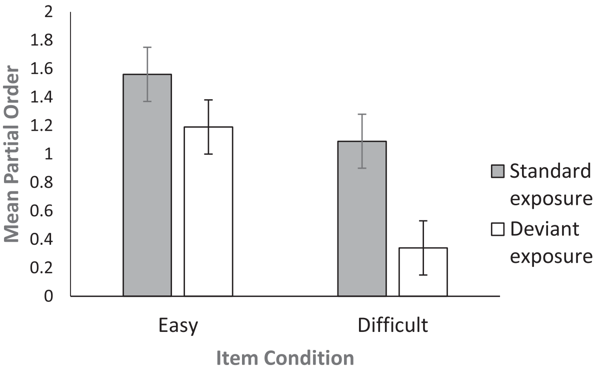

Figure 3. Mean partial order scores by condition.

Given that prior research (Loucks & Price, 2019) indicated that deviancy would have a more negative effect in the difficult than easy condition, we hypothesised that this relationship would also be present in the present data. Thus, despite the lack of significant interaction, this *a priori* hypothesis was further investigated using independent samples *t*-tests. In the easy condition, there was no significant difference in partial order scores between the standard and deviant conditions; $t(62) = 1.28$, $p = .204$, but in the difficult condition scores were significantly lower in the deviant condition, $t(62) = 3.36$, $p = .001$, Cohen's $d = 0.84$. Bayes factors on the easy condition also revealed weak evidence for the alternative hypothesis, in that the null was half as likely as the alternative, $BF_{10} = 0.511$, error % = 0.002 (Jarosz & Wiley, 2014). These results support the hypothesis that observing a deviant order hinders recall of action order, but does so to a greater extent when sequences involve items that are difficult to categorise.

Discussion

To become functional members of society there are countless multi-step action sequences people must acquire. A critical element of learning such sequences is the ability to learn the temporal order of events that unfold. Following Loucks and Price (2019), we hypothesise that accurate temporal encoding is only possible if one can first accurately identify each item that is involved in the sequence and identify what actions are being performed with each object. Relatedly, we also hypothesise that learning temporal order in novel action is difficult and/or highly sensitive to deviant input. In the present study, we found evidence to support both hypotheses.

The novelty of the current work is twofold, relative to Loucks and Price's (2019) results with children. First and foremost, we show here that these properties of temporal processing in action are present even in adults with comparatively sophisticated memory abilities. While the methodologies are not identical between the two studies, the patterns are nearly identical when the most critical experimental dimensions are maintained. Even though the categorisation manipulation is relatively subtle, it is enough to impair encoding of sub-actions and temporal order. And even though some participants in the easy-item condition saw a deviant order in the exposure phase, this did not significantly impact their recall of the standard order – indicating robust temporal encoding. This same deviant order in the difficult-item condition came close to eliminating recall of the standard order – indicating fragile temporal encoding. This indicates that the processing load in the initial item stage can impact downstream processing in the sub-action and order stages. Note that all participants were able to recall the individual items with equal facility. Thus, it was not the appearance of the items themselves that were difficult to encode or recall, but their higher-level semantic properties that are involved in the long-term storage of the sequence.

Second, the present results improve upon the methodology of Loucks and Price (2019) in that both the easy-item and difficult-item sequences were identical save for the items used. In Loucks and Price different sub-actions were executed in the easy-item and difficult-item sequences, since all children were taught both sequences on the first day. This decision provided a significant statistical advantage for child participants (within-subjects design), but rendered it difficult to draw firm conclusions about the items' effect on sub-action memory. In the present experiment the use of difficult as compared to easy items reduced participants' memory for individual sub-actions, even when they were identical. Thus, we can be certain that it is indeed the increased processing load at the item stage that reduces processing at both subsequent stages.

The theorised processing hierarchy that we evaluated here with adults, originally proposed by Loucks and Price (2019), was developed in order to explain how naïve individuals learn complex sequences of action. This occurs much more frequently for children than adults, but as indicated by the present data, adults' cognitive processing in such situations is similar to children's. Hasselmo and Stern (2006) proposed a theory of the physiological structure of working memory that distinguishes between working memory for familiar versus novel stimuli. When familiar stimuli are utilised in working memory tasks, frontal and parietal regions are required for active maintenance of information, but when novel stimuli are utilised parahippocampal regions are additionally recruited for maintenance. When individuals are learning novel sequential actions, they are clearly engaged in a more demanding cognitive process that requires more neurocognitive resources than when they are asked to learn the sequence of simple and familiar digits, numbers, or even spatial locations. The present experiment thus provides a snapshot of what observers are able to encode and retrieve in ecologically rich learning scenarios.

The present paradigm and effects share some similarities with the Hebb repetition effect (Hebb, 1961; Oberauer & Meyer, 2009), for which recall is better when sequences are surreptitiously repeated in learning. Recently, the Hebb effect was demonstrated in tactile sequence learning (Johnson et al., 2016). What is similar in our experiment is that order learning was better when all trials had identical order than when not. But there are notable differences as well. First, the typical Hebb paradigm is a contrast of some percentage of repeated trials (say 30%) vs. the remaining non-repeated trials, within subjects, whereas our paradigm compared 100% vs. 75% repeated trials, between subjects. Second, in the present research there were no identical learning trials – each trial involved new items in new positions. The repetition was in the abstract nature of the items – a potentially new direction for research in the Hebb effect literature. And finally, our data also demonstrate that order deviance selectively impacts order learning, as item and sub-action memory were unaffected by order deviance.

These results also have implications for working memory more broadly, as there are very few studies of memory for action. Wood (2007) provided evidence that individuals can maintain 2–3 individual action representations in a visual working memory (VWM) store that operates in a similar manner to VWM for objects and spatial locations. In Wood's experiments a single human figure executed miming actions with their body. Interestingly, in the current study memory for individual sub-actions, which involve two objects as well as a motor action, was also limited to an average of about 3 in the easy-item condition. These results suggest that object-oriented actions may utilise the same VWM system as miming actions, and that units can be a collection of bound features. But as the current study only assessed long-term recall, future research is needed to address whether this is actually a limit of VWM during encoding or instead related to retrieval processes operating on long-term memory.

Our conclusion that the effect of deviancy was weaker in the easy condition is somewhat weakened by the fact that there was no significant interaction in the factorial ANOVA. This is likely due to the high variance in cell means, as individual differences in recall were quite large. Replicating this effect with a larger sample, or with greater differences in item difficulty, or with alterations in the task that reduce variability in order scores are possible options for increasing confidence in this finding. It would also be of value in future research to directly compare children and adults with the same task and materials, to evaluate similarities and differences across development in learning order for novel sequential actions.

In summary, although we know that humans are quite good at learning order (Ghirlanda et al., 2017), we are just beginning to uncover how this feat is achieved. The current research indicates that adults' ability to learn action order is not qualitatively different from children's, despite significant advances in information processing. Adults, like children, find learning order difficult and are highly sensitive to deviant information when learning. However, lightening the cognitive load in the early stages of processing can protect memory in the face of such deviant information. These results represent an important step forward in understanding what may be one of humankind's most essential cognitive capacities.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, JL, upon reasonable request.

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