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Intrusions Into Script-Like Action Sequences: A Behavioral Investigation

Maomiao Peng, Mary A. Peterson, and Lynn Nadel
Department of Psychology, University of Arizona
Cognitive Science Program, University of Arizona

Prior knowledge can facilitate the learning of related material, while this new learning can itself modify the memory underlying that prior knowledge. Research on the flexibility of memory has concentrated on episodic memories (Hupbach et al., 2007), fear-related associations (Su et al., 2022), and categorical knowledge (Richter et al., 2019); little is known about the memories for structured action sequences. To address this, we trained participants on two minimal script-like action sequences containing repeated object pairs while manipulating two factors: the similarity between scripts (four vs. six repeated pairs) and the required action linking objects to target boxes into which they were to be moved (click vs. drag). We found that memory intrusions—recalling elements or subsequences from the later sequence when asked to recall the initial sequence—occurred not only for isolated elements but also as linked intrusions involving both object and location. These memory intrusions were more likely with six (vs. four) repeated pairs and when participants used the drag (vs. click) action. Experiment 2 tested whether the results of Experiment 1 could be replicated at the group level and assessed their stability across time at the individual level. While the basic results of Experiment 1 were replicated in Experiment 2, its results were less conclusive regarding whether memory intrusions reflect trait-like stability across time. Together, these findings demonstrated that intrusions into previously learned action sequences occur with new learning, highlighting the plasticity of memories involving script-like behaviors.

Public Significance Statement

It is well known that prior knowledge aids new learning. For instance, if you are an expert birdwatcher, you can easily learn and remember details about a bird you see while hiking if it belongs to a category you are familiar with. However, new learning does not always safeguard existing memories and can, at times, modify them. Research has shown this effect in the destabilization of emotional memories and established semantic memories, particularly those involving categories and concepts. Far less attention has been given to how new learning affects short, script-like action sequences—simple sequences of actions performed in a stable context. This study mainly investigates whether new learning can modify existing script-like action sequences and examines the factors influencing any such effects. We found that new information can alter linked steps within action sequences and that both the degree of similarity to the original action sequence and the type of actions involved in the sequences affect the changes.

Keywords: memory updating, interference, intrusion, action sequences, script

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Everyday tasks—from airline check-in and boarding to preparing a dish for a holiday gathering to responding to emergencies such as operating a fire extinguisher—often rely on well-practiced memory scripts. These cognitive frameworks, developed through repeated experience or training, enable individuals to perform familiar procedures efficiently and independently. However, scripts are not static. Developmental changes, technological shifts such as advances in artificial intelligence, and cross-cultural experiences frequently require people to adapt their familiar scripts to new contexts. A dinner in an unfamiliar cultural setting, for example, may follow a restaurant script that differs from one's own (Fivush & Grysman, 2023). Understanding memory scripts—particularly their capacity to adapt to changing circumstances—has significant practical implications.

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Mary A. Peterson https://orcid.org/0000-0002-6988-7119
Experiment materials, data, and analysis code are accessible on the Open Science Framework (https://osf.io/cqeks/). The data and ideas presented in this article were previously included in Maomiao Peng's doctoral dissertation.

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Correspondence concerning this article should be addressed to Mary A. Peterson or Lynn Nadel, Department of Psychology, University of Arizona, 1503 East University Boulevard, Tucson, AZ 85721, United States. Email: mapeters@arizona.edu or nadel@arizona.edu

Memory scripts are structured sequences of actions tied to particular contexts, typically characterized by temporal order, context specificity, and hierarchical organization (Abelson, 1981; Schank & Abelson, 1977). Within this hierarchy, smaller subscripts often serve as tightly linked units revolving around a shared core element—for instance, the sequence of actions applied to a toothbrush nested within the broader "getting up" script. Research shows that young infants begin to develop basic scripts, and by preschool age, children can use these scripts to predict events (Brubacher et al., 2018; Gönül et al., 2024; Mandler & Pagán Cánovas, 2014; Nelson & Gruendel, 1981). However, memory is flexible. Classic work on procedural memory, such as the finger-tapping task, demonstrates that reactivating a learned sequence—specifically, a fixed five-element motor pattern (e.g., 4-1-3-2-4)—can render it labile and susceptible to modification (Walker et al., 2003). Similarly, research on the misinformation effect shows that misleading postevent information can be incorporated into the recollection of an original event (Loftus, 2005).

These paradigms typically analyze performance in terms of independent units. For instance, in the finger-tapping task, performance is often evaluated using aggregate metrics—such as the overall proportion of errors or the number of complete sequences produced within a 30-s trial. By focusing on these measures, such analyses obscure the interdependencies between sequence elements, treating the steps as independent data points rather than parts of a linked chain. Similarly, false-memory paradigms often assess whether a single element of an episode is erroneously incorporated into recollection. It remains an open question, therefore, whether changes in retrieval occur independently at the level of isolated elements or whether these effects extend across the linked steps of the sequence. Our paradigm can begin to answer that question.

To address this gap, we developed a paradigm that targets the subscript level described above, using a stable contextual cue during action execution. Although classical scripts are richly contextualized, our use of simplified, minimal, and repeatable action sequences allows us to reduce the variability that typically accompanies naturalistic, multistep scripts, and achieve precise evidence of how linked actions are modified. Accordingly, we frame this as an investigation of "script-like action sequences" rather than canonical scripts. As shorthand to refer to these minimal, repeatable sequences, however, we use the term "script" in what follows.

Specifically, in Experiment 1, participants chose between two similar objects in a series of object pairs and then performed an action on the chosen object—placing that object into one of six boxes. Participants learned about 12 object pairs and the target boxes into which the correct object of each pair should be placed. After learning the first action script to criterion, a second script that shared the same context as the original action script was introduced. This second script also involved 12 object pairs, among which were some of the same object pairs used in the first script but with a change in both the correct choice of object in the pair and the location of the box into which that object should be put.

Crucially, although this operation shares similarities with procedural learning in that participants perform the same motor actions multiple times, its primary demands are mnemonic rather than motoric, as participants must explicitly retrieve both the correct object identity and its corresponding location within a stable context. This structure offers two theoretical advantages over procedural learning paradigms. First, the fixed temporal order goes beyond a simple object–location association. Because participants must decide which object to select before deciding which box to place it in, recall unfolds as an ordered sequence rather than as two independent choices. This structure permits examination of whether performance at the second step (box choice) depends on performance at the first (object choice). Second, the two steps presumably recruit distinct kinds of memory: Object selection draws on recognition memory for identifying the correct item, whereas box selection relies on spatial memory for its location. This distinction is informative because it allows us to ask whether performance in these domains is related within the same trial. Specifically, our paradigm makes it possible to examine whether an intrusion in one domain (object memory) is associated with an increased probability of an intrusion in the other domain (spatial memory). Evidence of such a conditional relationship would suggest that the two steps are not independent, suggesting that the short action sequences implemented in our task may be retrieved in an integrated manner rather than as isolated responses. While this paradigm does not test full cascading modifications in long, interdependent scripts—as such work would require richer narrative or goal-based structures—it offers a preliminary exploration of how overlapping action sequences interact, serving as a foundational baseline for future work on complex script updating.

When participants were tested on the first sequence after learning a second, partially overlapping sequence, they sometimes selected the object or box associated with the new sequence. We use the term "intrusion" to refer to erroneous selection of objects or target boxes learned in the second script when participants were prompted to make the choices corresponding to the first script. The term "intrusion" is used descriptively to maintain theoretical neutrality without assuming any specific explanatory mechanism, including reconsolidation (Hupbach et al., 2007; Nader et al., 2000; Haubrich et al., 2015; Lee et al., 2017; Schiller, 2022), interference (Dewar et al., 2007; McGeoch & McDonald, 1931; Müller & Pilzecker, 1900; Underwood, 1957), false-memory accounts (such as fuzzy-trace theory, Reyna & Brainerd, 1995, and the source-monitoring framework, Johnson et al., 1993), or state-dependent processes (Gisquet-Verrier et al., 2015; Millin et al., 2001). Intrusions in object selection or box location reflect modifications in object memory and spatial memory, respectively, while those involving both aspects indicate alterations in the script sequence, which we coded as "linked intrusions."

In Experiment 1, we used this script-like sequence paradigm to test whether new learning modifies previously acquired sequences by altering the selection of either objects, target boxes, or both in a linked manner, and to examine how two factors modulate them. The first factor is action type, which was manipulated by the means by which participants moved the selected object to the target box. Prior work shows that more engaged physical actions can enhance memory (Cohen, 1981; Engelkamp & Krumnacker, 1980; Roberts et al., 2022; Schwartz & Plass, 2014). Here, we hypothesize that higher levels of enactment may strengthen the associations between consecutive steps in a script, thereby increasing the likelihood of linked intrusions—intrusions of both object selections and target box locations. To test this hypothesis, we manipulated how participants moved objects into a box in our scripts—either by clicking the box location alone or by clicking on the object and dragging it to the correct box location—and assessed whether these different degrees of enactments (higher in the latter than the former condition) influenced the presence of script memory intrusions.

The second factor is similarity between scripts, which was manipulated by varying the number of repeated object pairs (four and six) between the first and second learned scripts. We hypothesized that increasing the number of repeated pairs would cause the scripts to be perceived as more similar or congruent, thereby increasing the likelihood that an existing schematic memory would be altered by the new memories.

Finally, Experiment 2 sought to replicate these group-level effects in a new sample and evaluate the test–retest stability of the intrusion measures at the individual level.

Experiment 1

Method

Participants

A total of 362 University of Arizona undergraduates were recruited for the study. Inclusion was based on a retention interval criterion: Participants were required to begin the second day's procedures 20–28 hr after concluding the first day's procedures, a range selected to maintain a retention interval of approximately 1 day. Eighty-six participants did not meet this criterion, resulting in a final sample of 276 participants. The sample was distributed across four experimental groups: Click-4 ($n = 69$; $M_{age} = 19.6$, $SD = 1.1$), Click-6 ($n = 69$; $M_{age} = 19.5$, $SD = 0.9$), Drag-4 ($n = 59$; $M_{age} = 19.1$, $SD = 1.1$), and Drag-6 ($n = 79$; $M_{age} = 19.1$, $SD = 0.9$).

Participants reported their gender via a free-response text box before the formal experiment. Gender data were properly recorded for 128 participants (107 identified as women and 21 as men); however, due to a technical storage error restricted to the Click-4 and Drag-6 conditions, gender information was unavailable for the 148 participants in these conditions. Race and ethnicity information were not collected in this study. We acknowledge the importance of including race and ethnicity measures in future research.

Procedure

All experimental procedures were approved by the University of Arizona's Institutional Review Board and were conducted with full informed consent from the participants. We developed a paradigm assessing memory for script-like action sequences within which we controlled two factors: the type of action involved in moving the selected object to a box and how similar the first and second scripts were to each other. Our paradigm allowed us to explore how individual components and sequences involved in scripts can be modified and to investigate the factors that drive the modification. We implemented four versions of the same study design, each involving three separate parts, as sketched in Figure 1A.

In the first part, on Day 1, participants were exposed to two concentric purple circles (inner circle: dark purple, outer circle: light purple) containing 12 pairs of objects peripherally positioned around these circles, one object of each pair in the inner circle and the other in the outer circle (Script 1). Figure 1B illustrates the layout of the circles, object pairs, and target boxes. Each object pair consisted of two exemplars of a basic-level category (e.g., two lamps). As can be seen in Figure 1B, the concentric circles contained 18 possible locations for the object pairs, with some positions left empty to avoid straightforward one-to-one mapping and increase cognitive load. On either side of the concentric circles, three target "boxes" were placed one above the other. The task for the participant was to choose the correct object from each pair and then allocate it to one of the six boxes along the sides.

There were two sessions on Day 1 for each of two scripts: a study session and a test session. In the study session, a visually distinct purple circle (one that contrasted sharply with the background in both saturation and brightness; see Figure 1B) around one of the two paired objects guided participants to the correct object, which they then "chose" by clicking the mouse on it. After the selection, a sentence, "put it here," appeared under one of the six boxes. Participants placed the object in the indicated target box in one of two ways: In the click condition, they simply clicked on the target box, and the program automatically placed the object inside. In the click-and-drag condition (often referred to as simply the drag condition), participants clicked the object and manually dragged it into the target box using the computer mouse. In both conditions, after the object appeared in the chosen box, a magician's hat covered the box for 5 s. When the hat was removed, the object had disappeared, leaving the box empty. Participants now had to select from the next pair of objects, until they had responded to all 12 object pairs, in clockwise order. This script was repeated three times to complete the study session on Script 1.

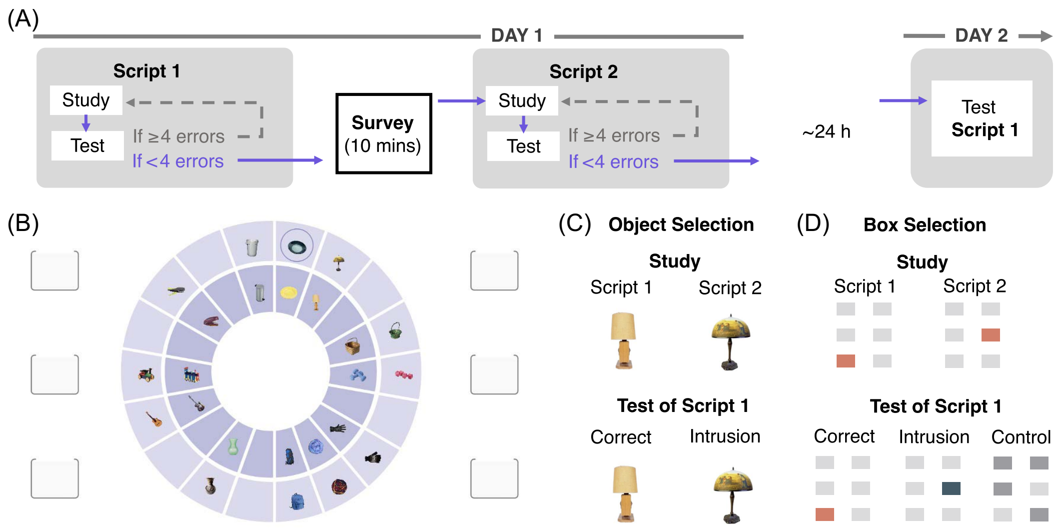
Next, participants moved to a rigorous test session. In the test session, participants moved around the circles in a clockwise order and responded to each object pair once. No hints were given about which object to choose or where to put it. Instead, after participants selected an object from each pair and placed it in a box, feedback was provided indicating whether their object and box choices were correct or incorrect. If they made four or more errors overall in the test session (including both object and target box choice), they were sent back for further study. At the end of each of these subsequent study sessions, participants decided whether to study again or to start the test if they felt ready to proceed. When they made fewer than four errors, they passed the test session. At this point, the program sent them to a questionnaire session concerned with autobiographical memory. This break lasted 10 min, even if they finished the questionnaire in less time.

Following the break on Day 1, participants moved to Part 2 of Day 1, in which they were presented with a new script (Script 2) with 12 pairs of objects, of which either four or six pairs were the same as on the first script. For these "repeated" object pairs, the one of the pair that was "correct" was switched (e.g., if the "correct" object was in the inner circle in Script 1, the "correct" object was in the outer circle in Script 2). The target box into which this object should be placed was also different from what it had been in Script 1. Participants went through the same study and rigorous test procedures for Script 2 as they had for Script 1. Participants completed the same action condition as in the first part. Within each action condition, they were divided into two groups: one in which four object pairs were repeated from the first part and another in which six object pairs were repeated (Click-4, Click-6, Drag-4, and Drag-6 conditions).

On Day 2, approximately 24 hr following their participation on Day 1, participants were subjected to a test procedure in which they were explicitly instructed to choose the object and target box pairings they had learned in Script 1. We assessed intrusions by analyzing participants' responses to the object pairs that were repeated in Script 2. For object selections, choosing the Script 1

Figure 1

Experimental Design for the Script-Like Sequence Paradigm



Note. Panel A shows the schematic procedure of the study. The experiment spanned 2 days. On Day 1, participants completed three initial study runs of Script 1, followed by a test with feedback. If they did not meet the accuracy criterion (<4 errors), they returned to the study phase before retesting. After reaching the criterion, they took a fixed 10-min break during which they completed an autobiographical memory survey, then learned Script 2 and were tested using the same criterion. On Day 2, participants completed a test on Script 1, using the same procedure as the poststudy test on Day 1 but without feedback. Panel B shows the study task and stimulus layout. The tasks utilized a display with two concentric purple circles containing object pairs and target boxes. In Script 1, participants learned to choose the correct object from each of 12 pairs and place it into the correct box location. A purple circle cue indicated the correct object during study trials. After selecting an object, a prompt reading "Put it here" appeared below one of the six boxes, and participants placed the object into that box by either clicking or clicking and dragging, depending on the assigned action condition. In each learning session, participants went through all 12 pairs in a clockwise sequence. In test stages, the same procedure was followed but without hints; feedback was provided after both object and box selections for a pair were completed. Script 2 contained some repeated object pairs (four or six shared with Script 1 but with different correct choices); the remaining pairs were novel. The study and test procedures for Script 2 were identical to those for Script 1. Panel C shows the two possible outcomes when participants select objects on Day 2. If the correct object from Script 1 is the left lamp and from Script 2 is the right lamp, then, when asked to recall Script 1's information, selecting the left lamp is correct, while choosing the right lamp is considered an intrusion choice. Panel D shows the three possible outcomes for box selection on Day 2. Given the instruction to recall the Script 1 information, selecting the box location from Script 1 is correct; selecting the box location from Script 2 is an intrusion choice; selecting some other box location is a control error. Additional details on the experimental conditions can be found in Supplemental Material S4. See the online article for the color version of this figure.

object was correct; choosing the Script 2 object was an intrusion. For box selections, choosing the Script 1 box was correct; choosing the Script 2 box was an intrusion, and selecting any of the four remaining boxes was coded as a control response (Figure 1C and 1D).

Analysis

Most variables were not normally distributed (further details, including skewness, kurtosis, and Shapiro–Wilk test results, are presented in Supplemental Material S1). Accordingly, the Wilcoxon signed-rank test was employed for comparisons to chance and between manipulated factors. Effect sizes were estimated using rank-biserial correlation (r_{bc}). For comparisons involving more than two variables within groups, Friedman tests with false discovery rate (FDR)-corrected post hoc Wilcoxon signed-rank tests were used. Effect sizes for the Friedman test were estimated using Kendall's *W*.

To test the interaction between action type (click vs. drag) and the number of repeated object pairs (four vs. six), we conducted bootstrapped analyses of variance (ANOVAs) with residual resampling ($B = 10{,}000$; lmboot, R), a procedure that yields robust estimates under nonnormal distributions. We chose this approach because standard nonparametric tests (e.g., Friedman) do not allow for the assessment of interaction effects in a 2 × 2 factorial design. Analyses were run separately for object and box selections across the four experimental conditions. Effect sizes are reported as partial η^2 (η_p^2).

To better interpret nonsignificant results, we additionally calculated Bayes factors using JASP (Love et al., 2019): We used BF_{excl} for ANOVAs, because it assesses whether excluding a factor improves model fit, and BF_{01} for pairwise comparisons, because it directly quantifies evidence for or against group differences (Keysers et al., 2020). By convention, BF_{excl} and BF_{01} values of 1–3 suggest weak support for the null, 3–10 indicate moderate evidence, and >10 imply strong support.

Transparency and Openness

This study was not preregistered. As this is the first study of script memory intrusions using our simplified paradigm, no prior effect sizes or meta-analytic effect sizes were available for reference. Therefore, the sample size for Experiment 1 was not determined using power analyses. However, the sample size for Experiment 2 was calculated based on the effect size obtained from Experiment 1. The objects we used were sourced from an image database (Konkle et al., 2010). The experiments were programmed using PsychoPy/JS (Peirce et al., 2019) and run with Pavlovia (https://pavlovia.org). Data were analyzed using Python (Version 3.10.3), R (Version 4.4.2; RStudio), and JASP (Version 0.18.1). Experiment materials, data, and analysis code are accessible on the Open Science Framework (https://osf.io/cqeks/, Peng et al., 2026).

Results

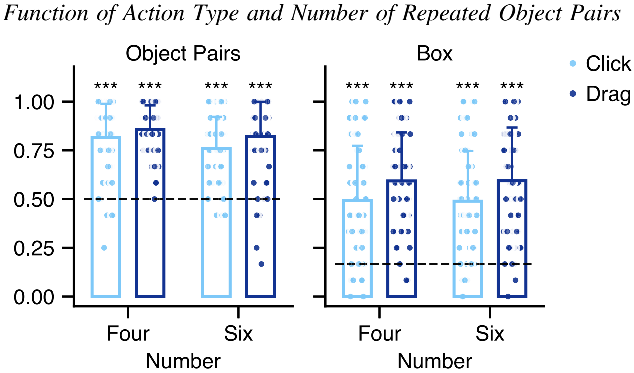
Accuracy

Memory for both objects and box locations was better than chance. Chance level was .50 for object selection, reflecting random choice between the two objects in each pair, and .167 for box selection, reflecting random choice among the six box locations.

Objects. Accuracy for all participants, for the 12 object pairs across the four conditions, was significantly greater than chance (0.81; Wilcoxon signed-rank test, $W = 34{,}685$, $p < .001$, $r_{bc} = 0.98$, one-sided). This was also the case for each of the four conditions considered separately (one-sided Wilcoxon signed-rank tests: Click-4: 0.82, $W = 2{,}255$, $p < .001$, $r_{bc} = 0.98$; Click-6—0.76, $W = 2{,}074$, $p < .001$, $r_{bc} = 0.99$; Drag-4: 0.86, $W = 1{,}711$, $p < .001$, $r_{bc} = 1$; Drag-6: 0.82, $W = 2{,}803$, $p < .001$, $r_{bc} = 0.97$; see Figure 2 left). To assess whether the type of action (click vs. drag) and the number of repeated object pairs (four vs. six) affected object choice, we compared accuracy for all object pairs using the data from all four conditions (click vs. drag; four vs. six repeated object pairs) in a bootstrapped ANOVA. Accuracy was significantly better in the drag condition than the click condition ($p = .02$, $\eta_p^2 = 0.02$, $M_{Click} = 0.79$, $M_{Drag} = 0.84$). Accuracy was significantly better for four rather than six repeated object pairs ($p = .02$, $\eta_p^2 = 0.02$, $M_{Four} = 0.83$, $M_{Six} = 0.79$). There was no interaction between action and number of repeated object pairs: $p = .57$, $\eta_p^2 < 0.01$, $BF_{excl} = 2.49$.

Figure 2

Experiment 1 Object Accuracy and Target Box Accuracy as a Function of Action Type and Number of Repeated Object Pairs



Note. The dashed line represents chance level. Error bars indicate the standard error. Light blue = click condition; dark blue = drag condition; left = object accuracy; right = target box accuracy. See the online article for the color version of this figure.
*** $p < .001$.

Target Boxes. Accuracy for the 12 choices of target boxes for all participants (0.54) was greater than chance (Wilcoxon signed-rank test, $W = 37{,}250$, $p < .001$, $r_{bc} = 0.95$, one-sided). This was true for each of the four conditions considered separately (one-sided Wilcoxon signed-rank tests—Click-4: $M = 0.49$, $W = 2{,}278$, $p < .001$, $r_{bc} = 0.89$; Click-6: $M = 0.49$, $W = 2{,}315$, $p < .001$, $r_{bc} = 0.92$; Drag-4: $M = 0.59$, $W = 1{,}758$, $p < .001$, $r_{bc} = 0.99$; Drag-6: $M = 0.59$, $W = 3{,}121$, $p < .001$, $r_{bc} = 0.98$; Figure 2 right). To assess the effect of the type of action (click vs. drag) and number of repeated object pairs (four vs. six) on accuracy for the 12 target box choices, we compared box choices using the data from all four conditions in a bootstrapped ANOVA. A significant action-related improvement was found: Accuracy was higher in the drag conditions than the click conditions ($p = .001$, $\eta_p^2 = 0.04$, $M_{Click} = 0.49$, $M_{Drag} = 0.59$). There were no effects of the number of repeated object pairs and no interaction between action type and the number of repeated object pairs—number of repeated object pairs: $p = .98$, $\eta_p^2 < 0.01$, $BF_{excl} = 10.04$; Action Type × Number of Repeated Object Pairs: $p = .96$, $\eta_p^2 < 0.01$, $BF_{excl} = 12.03$.

Effects of Action Type on Learning Times. For Script 1, participants required fewer training sessions in the drag condition (Click-4: 4.9; Drag-4: 4.5; Click-6: 5.5; Drag-6: 4.4), revealing a main effect of action type ($p = .001$). Dragging actions facilitated faster learning. For Script 2, we observed a significant interaction between action type and the number of repeated object pairs ($p = .02$). Although participants consistently learned faster with dragging, this advantage was more pronounced in the six repeated object pairs condition (Click-4: 3.6; Drag-4: 3.3; Click-6: 4.3; Drag-6: 3.3).

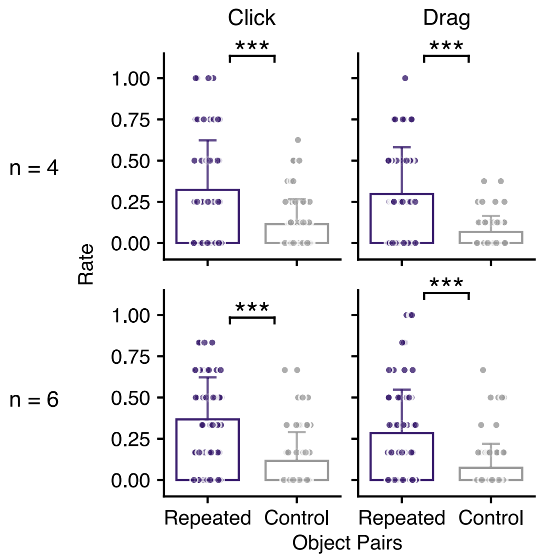
Object Intrusions

To evaluate the degree of memory intrusions for objects on Script 1 following exposure to Script 2, we examined how often participants erroneously selected the object from the critical repeated object pairs that was correct in Script 2, rather than the correct choice for Script 1. We tested whether they did this more often than they made errors on nonrepeated (control) object pairs. As Figure 3 shows, for repeated object pairs, 0.28–0.37 of the objects that were correct on Script 2 were erroneously selected as having been correct on Script 1. This percentage was significantly greater than the control error rates of 0.07–0.12, defined as the rate of choosing the incorrect object for the nonrepeated object pairs. The object intrusion rate was significantly greater than the control error rate in all four experimental conditions (Wilcoxon signed-rank test, Click-4: $W = 110$, $p < .001$, $r_{bc} = 0.84$; Click-6: $W = 143$, $p < .001$, $r_{bc} = 0.81$; Drag-4: $W = 62$, $p < .001$, $r_{bc} = 0.88$; Drag-6: $W = 36$, $p < .001$, $r_{bc} = 0.96$).

We compared the effects of action type and number of repeated object pairs on the object intrusion rate in a bootstrapped ANOVA. No significant effects were found ($p = .10$, $\eta_p^2 = 0.01$, $BF_{excl} = 2.95$; number of repeated object pairs: $p = .62$, $\eta_p^2 < 0.01$, $BF_{excl} = 9.59$; Action Type × Number of Repeated Object Pairs: $p = .39$, $\eta_p^2 < 0.01$, $BF_{excl} = 23.83$).

Figure 3

Experiment 1 Object Intrusion and Control Object Error Rates as a Function of Action Type and Number of Repeated Object Pairs



Note. Purple outlined bars show the rate of selecting Script 2 objects for repeated object pairs (object intrusion rate). Gray outlined bars show the rate of selecting incorrect objects for nonrepeated object pairs (control error rate). Error bars indicate the standard error, and dots represent the individual participants. Left = click action; right = drag action; top row = four repeated object pairs; bottom row = six repeated object pairs. See the online article for the color version of this figure.
*** $p < .001$.

Box Intrusions

To evaluate the degree of memory intrusion for target box locations on Script 1 following exposure to Script 2, we analyzed the rate of selecting, for the repeated objects, the target box that was correct on Script 1 (the correct box), the box that was correct on Script 2 (i.e., the intrusion box), or any of the other four boxes (control boxes). Results are shown in Figure 4. Friedman tests showed different likelihoods of these three box selections ($ps < .001$, Kendall's $W = 0.34$–0.51). Post hoc tests showed that in all four conditions, the correct box was chosen more often than the intrusion box or a control box (Wilcoxon signed-rank test, all $ps < .001$, $g = 1.45$–2.52; FDR corrected). The intrusion box was chosen more often than a control box in the six repeated object pairs conditions ($ps < .05$, $g = 0.50$–0.98; FDR corrected), but not in the four repeated object pairs conditions ($ps > .05$, $g = 0.15$–0.26; FDR corrected). Detailed statistical results can be seen in Supplemental Material S2.

Next, we used a bootstrapped ANOVA to examine the effects of action type (click vs. drag) and number of repeated object pairs (four vs. six) on box intrusion rate. We found a significant effect of number of repeated object pairs ($p = .01$, $\eta_p^2 = 0.03$): The intrusion box was chosen more often when there were six repeated object pairs rather than four ($M_{Six} = 0.17$, $M_{Four} = 0.12$). The main effect of action type was not significant ($p = .25$, $\eta_p^2 < 0.01$, $BF_{excl} = 5.78$), nor was the interaction between action type and number of repeated object pairs ($p = .27$, $\eta_p^2 < 0.01$, $BF_{excl} = 5.79$).

We also employed a second control condition to comprehensively examine box choices. This second control condition compared the box intrusion rates for repeated object pairs with the error rates (e.g., incorrectly chosen boxes) for nonrepeated control object pairs and again found no significant differences in the four repeated object pairs condition ($ps > .05$, $r_{bc} = 0.14$–0.22, $BF_{01} = 1.77$–3.49). Mirroring what was observed with the first control comparison, in the six repeated object pairs condition, the box intrusion rate for the repeated object pairs was higher than the box error rate for the control nonrepeated object pairs ($ps < .05$, $r_{bc} = 0.32$–0.75). For detailed statistical results, see Supplemental Material S2.

Linked Intrusions of Objects and Boxes

We further evaluated the extent to which participants jointly showed intrusions of boxes when they showed intrusions of objects. This test gets at the essence of script intrusion because scripts involve sequential actions, in this case the action of choosing an object and then placing it in a particular box. In the click action condition, the rate of choosing the intrusion box did not differ as a function of whether participants chose the correct object or the intrusion object (Figure 5 left; Wilcoxon signed-rank test, $W = 56$, $p = .19$, $r_{bc} = 0.35$, $BF_{01} = 3.20$; $W = 159$, $p = .08$, $r_{bc} = 0.36$, $BF_{01} = 2.11$, for four and six repeated object pairs, respectively). In the click-and-drag action condition, however, the rate of choosing the intrusion box was higher when participants chose the intrusion object rather than the correct object (Figure 5 right; Wilcoxon signed-rank test, $W = 22$, $p = .02$, $r_{bc} = 0.68$; $W = 149$, $p = .001$, $r_{bc} = 0.60$, for four and six repeated object pairs, respectively). Thus, dragging objects to their correct box locations increased the likelihood that object and box intrusions would be linked.

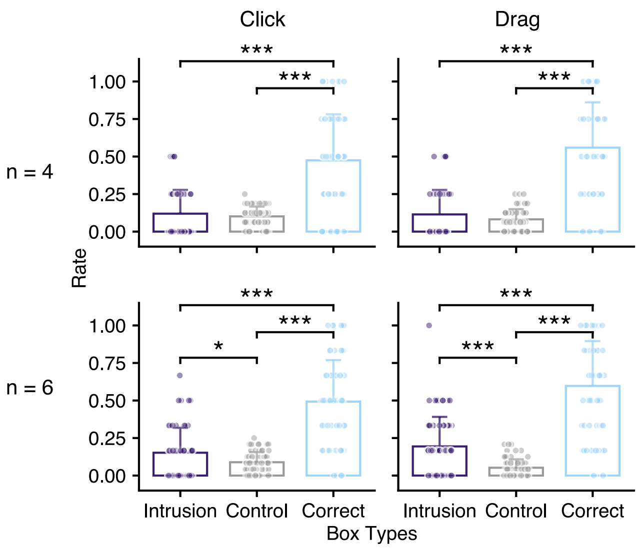
To further test the effects of action type (drag vs. click) and the number of repeated object pairs (four vs. six) on box intrusion rates when object memory intrusions occurred, we used a bootstrapped ANOVA. Participants who did not show any object intrusions were excluded from this analysis, as linked intrusion rate cannot be computed when no object errors are present. Such exclusions are necessary to ensure the validity and interpretability of the resulting indices. (The number of subjects remaining in each condition was as follows: Click-4, $N = 46$; Click-6, $N = 58$; Drag-4, $N = 37$; and Drag-6, $N = 60$.) We found that the linkage of object and box intrusion was significantly greater for drag than click actions ($p = .01$, $\eta_p^2 = 0.03$, $M_{Drag} = 0.32$, $M_{Click} = 0.19$). The ANOVA showed no effect of number of repeated object pairs ($p = .15$, $\eta_p^2 = 0.01$, $BF_{excl} = 2.71$) and no interaction between action type and number of repeated object pairs ($p = .36$, $\eta_p^2 < 0.01$, $BF_{excl} = 3.71$). These results again indicate that linked intrusions of objects and boxes depend on the type of action involved. With the hypothesized greater level of enactment, as in clicking and dragging compared to clicking, the likelihood of linked intrusions increases.

Experiment 1 Discussion

In this study, we trained participants on one script-like action sequence and subsequently introduced another script-like action sequence in which some elements were repeated from the first. We found that the intrusion rate for repeated object pairs was significantly higher than the error rate for nonrepeated (control) pairs regardless of action type (click vs. drag) or the number of repeated

Figure 4

Experiment 1 Rate of Box Choices as a Function of Action Type and Number of Repeated Object Pairs



Note. The bar labeled "Intrusion" shows the rate of selecting the box that was the correct target location for the paired object in Script 2. The bar labeled "Control" shows the rate of selecting a box that was not used as the correct location for an object in either Script 1 or Script 2. The bar labeled "Correct" shows the rate of selecting the box that was the correct location for the object in Script 1. Error bars indicate the standard error, and dots represent the individual participants. Left = click; right = drag; top = four repeated object pairs; bottom = six repeated object pairs. See the online article for the color version of this figure.
* $p < .05$. *** $p < .001$.

object pairs (four vs. six). Box intrusion occurred when six—but not four—objects were repeated, indicating that greater overlap of the items shown in Scripts 1 and 2 increased susceptibility to intrusion. Linked intrusions were observed in the drag condition but not in the click condition. These findings, obtained with small sequences embedded within larger, less cohesive sequences, lay the groundwork for future research on how larger sequences are affected by subsequent learning. Our study is the first to demonstrate that both script elements (objects or boxes) and script sequences (objects and their linked boxes) can be modified by subsequent learning. The ability to modify script-like sequences is important because it allows us to alter our predictions and actions across the varied situations that reflect the complexity of daily life.

Experiment 2

In Experiment 1, clear intrusion effects were evident with six repeated items in the click-and-drag condition. In Experiment 2, we aimed to test the robustness of this effect by replicating it in a new group of participants. For this purpose, we selected the experimental condition that yielded a substantial effect in Experiment 1 (i.e., the click-and-drag condition with six repeated items), ensuring sufficient trial numbers for stable measurement. In addition to determining the reliability of the group-level effects observed in Experiment 1, in Experiment 2, we sought to evaluate the test–retest reliability of key behavioral measures, including accuracy and intrusion rates, within individuals across repeated sessions. To this end, participants completed the paradigm twice, each time with novel stimuli, separated by a 1-week interval. This second objective is related to the "reliability paradox" (Hedge et al., 2018), whereby classic experimental paradigms—such as the Flanker task—can produce robust group-level effects when between-subject variance is minimized, thereby limiting the ability to observe individual differences. Therefore, Experiment 2 helps distinguish between competing interpretations of potential outcomes by dissociating group-level replicability from individual-level test–retest reliability. Specifically, (a) high individual-level reliability (e.g., a high repeatability index) would be consistent with the interpretation that the propensity for script modification reflects a stable individual trait. (b) Conversely, low individual-level reliability implies two distinct possibilities depending on the group-level outcome. If low reliability is accompanied by a failure to replicate the group effect, it would point to a transient or noisy phenomenon. However, if we observe a robust, replicated group effect along with low individual reliability, this pattern would align with the "reliability paradox." Such a dissociation would suggest that, although the phenomenon is robust at the population level, the metric used to assess memory may not afford sufficient between-subject variability for reliable individual-differences investigation.

Method

Participants

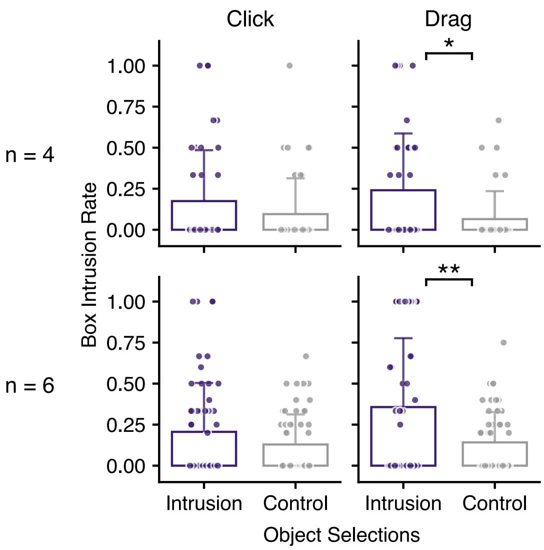
We calculated the required sample size for detecting an intrusion effect using G*Power 3.1 (Faul et al., 2007), based on the Experiment 1 Drag-6 condition effect size as this design will be used in Experiment 2. For a conservative estimate, we used the linked intrusion effect size ($r_{bc} = 0.60$) as this was the smallest effect size among the three intrusion effects (object intrusion, box intrusion, linked intrusion). To achieve a significant intrusion effect ($\alpha = .05$) with 95% power, 45 participants are needed. Anticipating some exclusions, we recruited 75 undergraduates from the University of Arizona to ensure an adequate sample size. Twenty-one participants were excluded for not performing the Day 2 test within the required timeframe, specifically 20–28 hr between learning Scripts 1 and 2 on Days 1 and 2, and Scripts 3 and 4 on Days 3 and 4. The final analysis included 54 participants (M_{age} = 19.1, SD = 1.9). Of these, 42 participants identified as women and 12 identified as men.

Procedure

All experimental procedures were approved by the University of Arizona's Institutional Review Board and were conducted with full informed consent from the participants. Experiment 2 consisted of two phases separated by 1 week (see Figure 6). In Phase 1, participants learned objects and their target box locations in two scripts (Scripts 1 and 2) within the context of two concentric purple circles as in Experiment 1 (six repeated object pairs, drag action condition) and were tested on object and target box locations learned in Script 1. One week later, in Phase 2, participants learned new object pairs

Figure 5

Experiment 1 Linked Intrusion Rates as a Function of Action Type and Number of Repeated Object Pairs



Note. The bars labeled "Intrusion" show the box intrusion rate on trials in which an intrusion object was selected. The bars labeled "Control" show the box intrusion rate on trials in which the correct object was selected. Error bars indicate the standard error, and dots represent the individual participants. See the online article for the color version of this figure.
* $p < .05$. ** $p < .01$.

and their target box locations in Scripts 3 and 4, following the same procedure as in Phase 1. Six object pairs from Script 3 were repeated in Script 4. Participants were asked to recall the object and target box locations learned in Script 3.

Analysis

To verify the replicability of Experiment 1, we first computed accuracy and intrusion rates for objects and target boxes for Phases 1 and 2, respectively. Then, consistency across phases was evaluated by calculating repeatability with linear models, incorporating "phase" as a fixed effect and "individual" as a random effect, and employing 1,000 bootstraps for 95% confidence intervals using R's rptR package (Nakagawa & Schielzeth, 2010; Stoffel et al., 2017). Prior to computing repeatability, an arcsine transformation was applied to the proportion data, as recommended by Sokal and Rohlf (1995). Repeatability (R) was defined as the ratio of between-subject variance to total variance, which includes both between-subject and within-subject variance (Nakagawa & Schielzeth, 2010; Sokal & Rohlf, 1995). A higher R value indicates greater consistency between phases.

Bayes factors (BF_{01} and BF_{excl}) were reported for nonsignificant results as in Experiment 1. However, Bayes factors were not calculated in the repeatability analysis.

Results

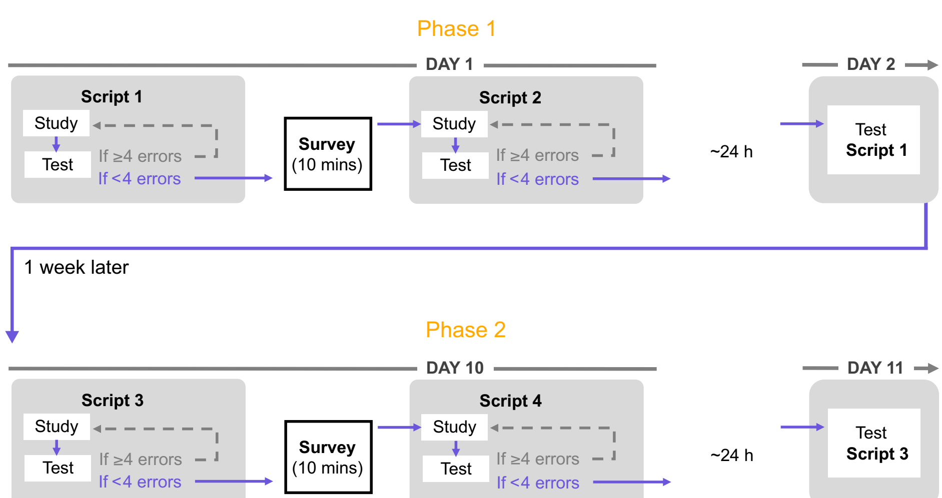
In Experiment 2, we found that the object intrusion rate, the target box intrusion rate, and the linked object and box intrusion rates successfully replicated the results of Experiment 1, in both Phase 1 and Phase 2.

Accuracy

Objects and Boxes. Mean object selection accuracy (Phase 1: 0.82; Phase 2: 0.75) and target box location accuracy (Phase 1: 0.54; Phase 2: 0.40) were significantly above chance, as shown by Wilcoxon signed-rank tests (Phase 1—object pairs: $W = 1{,}430$, $p < .001$, $r_{bc} = 1$;

Figure 6

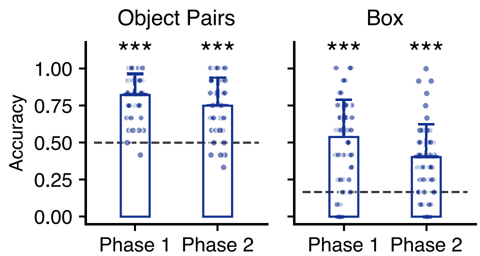
Experimental Design for the Two-Phase Script-Like Sequence Paradigm With 1-Week Interval



Note. This study involved two phases, separated by a 1-week interval. Both Phase 1 and Phase 2 utilized the basic experimental design from Experiment 1, but only the drag condition with six repeated object pairs was tested. The object pairs used in Phase 1 and Phase 2 were completely different to minimize interference between the two phases. On the second day of Phase 1, Script 1 was tested, and on the second day of Phase 2, Script 3 was tested. See the online article for the color version of this figure.

Figure 7

Experiment 2 Object Accuracy and Target Box Memory Accuracy as a Function of Phase (1 vs. 2)



Note. Bars represent the mean accuracy. Error bars indicate the standard error, and dots represent the individual participants. See the online article for the color version of this figure.
*** $p < .001$.

box locations: $W = 1{,}448$, $p < .001$, $r_{bc} = 0.95$; Phase 2—object pairs: $W = 1{,}344$, $p < .001$, $r_{bc} = 0.95$; box locations: $W = 1383.5$, $p < .001$, $r_{bc} = 0.86$; one-sided; see Figure 7).

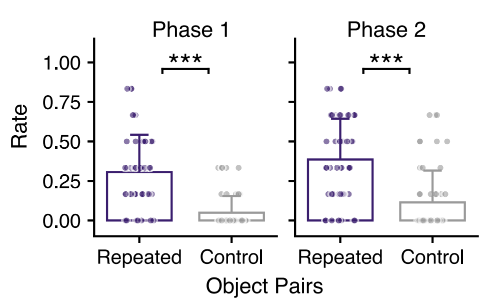
Object Intrusion, Box Intrusion, and Linked Intrusion

In both Phase 1 and Phase 2, when asked to recall objects from Script 1 in Phase 1 or Script 3 in Phase 2, participants more frequently misidentified objects from the critical repeated pairs in Script 2 (Phase 1) or Script 4 (Phase 2) than objects from the control nonrepeated pairs. As shown in Figure 8, participants selected the intrusion object from repeated pairs significantly more often than they made errors on nonrepeated (control) object pairs (Phase 1: $W = 32$, $p < .001$, $r_{bc} = 0.93$; Phase 2: $W = 68$, $p < .001$, $r_{bc} = 0.87$), indicating that memory intrusions were observed for objects.

Significant differences were observed in the rates of selecting the correct box, the Script 2/Script 4 box (i.e., intrusions), or a box that had not been paired with the chosen object (i.e., a control box)

Figure 8

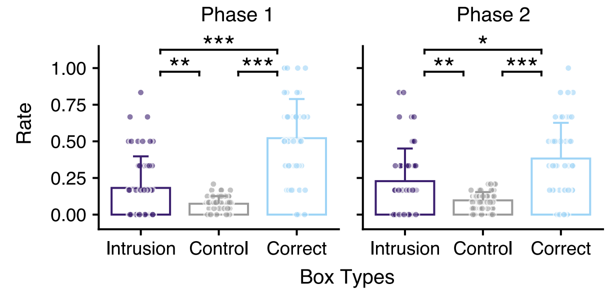
Experiment 2 Object Intrusion and Control Object Error Rates as a Function of Phase (1 vs. 2)



Note. The column labeled "Intrusions" shows the rate of selecting Script 2 (Phase 1) or Script 4 (Phase 2) objects from the repeated pairs rather than Script 1 (Phase 1) or Script 3 (Phase 2) objects as instructed. The columns labeled "Control" show the rate of errors on nonrepeated (control) object pairs. Error bars indicate the standard error, and dots represent the individual participants. See the online article for the color version of this figure.
*** $p < .001$.

Figure 9

Experiment 2 Rate of Box Choices as a Function of Phase (1 vs. 2)



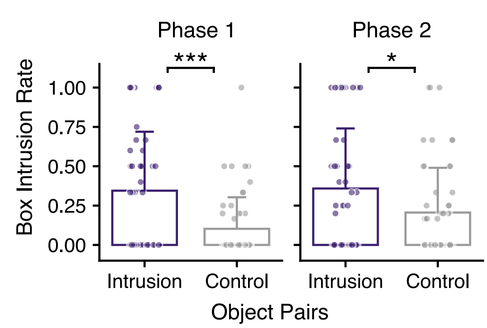
Note. Bars labeled "Intrusion," "Control," and "Correct" show the proportions of intruded, control, and correct box selections, respectively. Error bars indicate the standard error, and dots represent the individual participants. See the online article for the color version of this figure.
* $p < .05$. ** $p < .01$. *** $p < .001$.

in both phases (*ps* < .001; for detailed statistical results, see Supplemental Material S3). A correct box was a more likely choice than an intruded box, *ps* < .05, or a control box, *ps* < .001, and an intruded box was a more likely choice than a control box in both phases (Phase 1: $W = 298$, $p = .003$, $g = 0.68$; Phase 2: $W = 294$, $p = .001$, $g = 0.80$; FDR corrected; Figure 9), indicating memory intrusions were observed for boxes. (The box intrusion rate for the repeated object pairs was also higher than the box error rate for the control nonrepeated object pairs; for detailed statistical results, see Supplemental Material S3.)

As can be seen in Figure 10, the rate of box intrusions was higher when object intrusions occurred for repeated objects (linked intrusions) rather than when the repeated objects were correctly recalled from Script 1 (Phase 1) or Script 2 (Phase 2) in both phases (Phase 1: $W = 30$, $p < .001$, $r_{bc} = 0.82$; Phase 2: $W = 137$, $p = .03$, $r_{bc} = 0.45$). Thus, linked object–box intrusions in script memory occurred in both phases of Experiment 2.

Figure 10

Experiment 2 Linked Intrusion Rates as a Function of Phase (1 vs. 2)



Note. The bars labeled "Intrusion" show the box intrusion rate on trials in which an intrusion object was selected. The bars labeled "Control" show the box intrusion rate on trials in which the correct object was selected. Error bars indicate the standard error, and dots represent the individual participants. See the online article for the color version of this figure.
* $p < .05$. *** $p < .001$.

We also examined whether there were differences in participants' performance across the two phases of Experiment 2 by comparing object and box selection accuracy, as well as intrusion indices between the two phases. Surprisingly, our analysis indicated a decline in object and target box accuracy in Phase 2 (object accuracy: $W = 274$, $p < .01$, $r_{bc} = 0.47$; target box accuracy: $W = 239$, $p < .001$, $r_{bc} = 0.58$; compare Figure 5A and 5B). Nevertheless, as seen in Figure 5C–5E, there were no significant differences in the rates of object intrusions ($W = 371$, $p = .10$, $r_{bc} = 0.28$, $BF_{01} = 1.25$), box intrusions ($W = 399$, $p = .51$, $r_{bc} = 0.12$, $BF_{01} = 4.55$), or linked intrusions ($W = 253$, $p = .63$, $r_{bc} = 0.10$, $BF_{01} = 4.98$) between the two phases of Experiment 2.

Individual-Level Test–Retest Reliability

In Experiment 2, individuals' accuracy in selecting both objects and target boxes from Script 1 was repeatable across phases (Phase 1, Phase 2; object accuracy: $r = 0.41$, 95% CI [0.18, 0.62], $p < .001$; target box accuracy: $r = 0.48$, 95% CI [0.27, 0.66], $p < .001$). In addition, object memory intrusion rate was repeatable across phases ($r = 0.27$, 95% CI [0.02, 0.49], $p = .023$). In contrast, neither target box intrusion rate nor linked object and box intrusion rate was repeatable across phases ($rs < 0.01$, $ps > .05$). Thus, this repeatability analysis suggests that memory for objects and target boxes from Script 1 and Script 3, as well as the intrusions of Script 2 and Script 4 objects into those memories, might reflect traits of the participants. The lack of correlation across phases for target box intrusions and linked object and target box intrusions might initially suggest that these intrusions are driven by transient states. However, the variance structure of our data suggests an alternative explanation related to the psychometric properties of the task.

Crucially, tasks designed for group/condition comparisons—like the one we used here—may not effectively capture individual differences due to insufficient between-subject variance. Specifically, we assessed consistency between participants' performance across phases using repeatability, as the ratio of between-subject variance to total variance, including both within- and between-subject variance. When between-subject variance is small, even modest within-subject variance can significantly influence the total variance, reducing the ability to detect reliable individual differences. In Experiment 2, between-subject variance for target box intrusions and linked intrusions was <.01, making it difficult to detect individual differences, whereas it was 0.40, 0.45, and 0.26 for object accuracy, box accuracy, and object intrusion rate, respectively, providing greater opportunity to detect reliable individual differences. This aspect of our results may account for the failure to find evidence of repeatability.

To evaluate performance consistency from Phase 1 to Phase 2 without between-subject variance effects, we calculated difference scores for object accuracy, box accuracy, object intrusion, box intrusion, and linked intrusion. A priori, we classified a change greater than ±0.25 as inconsistent performance; otherwise, performance was considered consistent across the two phases. The proportions of participants with consistent performance were 83.3% for object accuracy, 64.8% for box accuracy, 61.1% for object intrusions, 57.4% for target box intrusions, and 34.1% for linked object and target box intrusions. Some participants even showed no difference across phases, with identical scores in both phases: 16.7% for object accuracy, 13% for box accuracy, 16.7% for object intrusions, 22.2% for target box intrusions, and 19.5% for linked object and target box intrusions. These results suggest that at least some participants exhibited stable, trait-like performance across both phases in memory accuracy, intrusion tendency, or both.

Experiment 2 Discussion

In Experiment 2, we examined whether the results of Experiment 1 could be replicated at the population level and whether intrusions in script-like action sequences reflect a stable trait at the individual level. We focused on the six repeated objects in the drag condition from Experiment 1—the condition that produced the strongest intrusion effects. First, the results of Experiment 2 robustly demonstrated strikingly similar measurement outcomes to Experiment 1, showing that memories for script elements (object selections and box selections) and script-like sequences can be modified. Second, we found evidence for trait-like effects in memory for objects and boxes, as well as in intrusions in object pairs. However, evidence for intrusions in box locations, whether linked to intruded objects or not, was inconclusive. Thus, while memory accuracy displays trait-like stability, the low reliability of the main intrusion metrics aligns with the "reliability paradox" (Hedge et al., 2018), suggesting that the linked intrusion effect is a robust population-level phenomenon, even though the current metric provides insufficient between-subject variance to reliably capture individual differences.

General Discussion

Script-like action sequences serve as simplified models for understanding how we internalize and update routine procedures. In Experiment 1, we show that memories for these sequences can be modified when new, related information is learned. Participants revised both the elements (objects and target boxes) and their sequences after encountering a second script that repeated certain object pairs but changed which items were chosen and where they were placed. As possible factors affecting these results, we examined script similarity (four vs. six repeated pairs) and type of action (click vs. click-and-drag) that was used to place the objects in their target boxes. Our findings show that (a) sequence-level memory intrusions (i.e., linked object and target box intrusions) were more common under the click-and-drag condition than the click alone condition and (b) higher similarity resulted in more target box intrusions, whereas accurate object memory was unaffected by these factors. Experiment 2 replicated the intrusion effects observed in Experiment 1 and revealed trait-like consistency in object memory intrusions, while the nature of box and linked intrusions remained unclear, likely reflecting limited between-subject variance in the present measure. Together, these findings confirm the modifiability of script-like action sequences and highlight the critical influence of action-based engagement in script revision.

Differences in Linked Intrusion Patterns Across Action Types

Script sequence intrusions, defined as the linked intrusion of objects and their target boxes, were examined under two action conditions that linked objects and target box locations—*clicking* the assigned box location or *clicking and dragging* the object to its assigned box. Script intrusions were observed exclusively in the latter condition, indicating that increased enactment through dragging promotes integrated script representations.

Although our findings align with an enactment account, the action manipulation itself introduces additional factors worth considering. Dragging requires participants to physically move the object into the box, whereas clicking produces automatic movement. This extra motor step may strengthen object–location binding, enhancing memory and making it more likely that, when an intrusion of the object occurs, the corresponding box location also shows an intrusion. Importantly, the novelty of our study lies in demonstrating that the impact of increased enactment—and the strengthened object-location binding it is likely to promote—extends beyond accuracy: It also contributes to linked intrusions in script-like sequence memory, connecting motor engagement and associative binding to distortions in how short action sequences are retrieved.

In addition, clicking on the object before dragging it to the chosen box, compared to clicking on the box location alone, may enhance participants' attention to the objects and the box associations, as reflected in higher accuracy in drag conditions compared with the click conditions. This improved accuracy likely reduces the selection of control boxes, thereby increasing the proportion of linked intrusions by promoting the selection of intrusion boxes and correct boxes, even when object memory performance remains comparable.

As noted in the introduction, scripts are hierarchically structured, comprising smaller sequences embedded within larger ones. Smaller sequences, such as selecting and placing an object into a box, are tightly linked and thus exhibit strong cohesion. In contrast, larger sequences—composed of these smaller units—are less cohesive, particularly when causal relationships are lacking, and their structure depends more on shared context than on direct content connections. Here, we focused on smaller sequences to establish how memory modification functions in strongly connected units, paving the way for future studies exploring the dynamics of weaker, larger scale sequences.

Similarity Increases Spatial Intrusions

Spatial memory intrusion was indexed via target box intrusion. We found that target box intrusion occurred when six—but not four—objects were repeated. With six repeated object pairs, more box locations were associated with the same object pairs. Specifically, in our paradigm, participants learned 12 object–target box associations in Scripts 1 and 2. When four object pairs were repeated between the two scripts, only four object–box associations shared the same object pairs across scripts. However, with six repeated pairs, this number increased to six. As a consequence, with six repeated objects, the two scripts were more similar and the later script was more likely to be perceived as a variant of the first. This similarity facilitates the modification of the existing memory rather than the creation of a new one.

An argument that might be raised against our claim is that increasing the number of repeated object pairs simply increases the opportunities for intrusion. For example, if a given individual had an 80% likelihood of intrusion, four repeated object pairs would typically result in three intrusions, while six repeated object pairs would more typically yield five intrusions. This alternative interpretation cannot explain our results, however, because we analyzed intrusion rates—ratios of intrusions to total repeated object pairs—rather than simply the number of intrusions. Consequently, it is unlikely that the rise in box intrusion rates in the six repeated object pairs conditions is due to increased intrusion opportunities.

It is important to note that similarity includes two dimensions. In this study, we focused on the quantitative aspect, examining whether increasing the number of repeated object pairs affects the likelihood of intrusions. As previously mentioned, scripts with six repeated pairs were more likely to be perceived as closer variations of the original script than those with four, and our data confirmed this, showing significantly more intrusions for target box locations in the six-pair condition. Another important dimension is a qualitative one, which relates to the distinctiveness of the items. For instance, using repeated object pairs involving a standing lamp and a table lamp (less similar) instead of two highly similar table lamps, as in this study, could make it easier for participants to differentiate between which objects were correct in the two scripts and potentially reduce intrusions. This qualitative aspect of similarity warrants further investigation in future research.

Object Memory Intrusions Occur Across Conditions

Across all experimental conditions, we found that the intrusion rate for repeated object pairs was significantly higher than the error rate for nonrepeated (control) pairs. Thus, for many participants, correct objects in the first sequence were affected in memory by the correct objects from the second sequence. These results align with previous research showing that when a new list of objects was learned after reactivating a previously learned list, objects from the second list were mistakenly integrated into the memory of the first list (Hupbach et al., 2007). While we did not prompt participants to recall the first script during the learning of the second script, as Hupbach et al. (2007) did, we used the same context (purple concentric scripts on the screen) to implicitly reactivate the original memories. Earlier findings from our lab (Hupbach et al., 2008) suggest that having identical large-scale spatial contexts across learning conditions was important for such intrusions because context reactivated the previously learned list when a new list was learned and this reactivation was essential for the presence of intrusions. Our present study shows that the local context displayed on the experiment computer screen can also serve as a cue to reactivate the original memory. In the future, it would be interesting to cross large-scale and local contexts to test how they interact.

A potential concern is whether participants learn the correct object in Script 2 by learning a metarule to select the alternative object, given that the correct object in Script 2 is the incorrect one in Script 1. If so, two scenarios are possible. First, participants might suppress Script 1 memories while learning Script 2. This aligns with one of the study's proposed mechanisms (see below)—that new learning could inhibit the original memory representation, even as it may coexist with updates to the original memory traces. Second, participants might retain only Script 1 memories if they assume that Script 2 simply requires selecting the other object. This would lead to fewer Script 2 intrusions during Script 1 recall, as participants would not effectively learn Script 2. However, our data show Script 2 intrusions, ruling out this possibility. Thus, metalearning is unlikely to significantly impact our findings.

What Drives Intrusion?

We used the term "intrusion" to describe the phenomena in which participants mistakenly recall information from Script 2 when asked to retrieve the original Script 1 memory. A central question is what drives these intrusions.

One possibility, in line with reconsolidation theory (Haubrich et al., 2015; Lee et al., 2017; Nader et al., 2000; Schiller, 2022), is that the original memory is updated, in that the Script 1 memory is overwritten by Script 2 content. However, the field of memory reconsolidation, from theoretical studies on updating mechanisms and clinical applications for disorders such as posttraumatic stress disorder and addiction, faces a joint challenge of defining boundary conditions for reconsolidation (Schiller, 2022; Schroyens et al., 2023). Factors like the age of the memory, the strength of initial training, and the degree of mismatch between new and preexisting memories are often poorly specified. This lack of specificity regarding boundary conditions has prompted critiques of reconsolidation theory, with critics arguing that nonsignificant results are sometimes attributed to the failure to meet these boundary conditions (Schroyens et al., 2023). On the other side, developing standardized operational criteria is hindered by variations in required conditions across studies, such as memory age. For instance, in one study, reconsolidation was absent when subjects were reminded 2 weeks after learning (Eisenberg & Dudai, 2004), but in another study, it was observed up to 3 weeks later and even up to 8 weeks later with extended context reexposure (Suzuki et al., 2004; for a review, see Schroyens et al., 2023). Our findings raise the possibility that such variations across studies might be related to the type of memories being investigated. Under some conditions, we observed updating (termed "intrusion" here) of object memory in the absence of any updating of memory for target box location. Further, whether or not we observed linked updating involving both objects and actions depended on the type of action participants performed while learning the scripts. Considering the specific type of memory under investigation when formulating boundary conditions could be beneficial.

Alternatively, as proposed by interference accounts, original and new memories could coexist and the erroneous recall of Script 2 content could occur because this newer information interferes with the original memory at the time of test. Reconsolidation and interference theories differ in whether altered memory can be recovered. Original memories inhibited by interference at test may reappear over time, while updated memories are permanently disrupted and cannot return (Clem & Schiller, 2016). However, a fundamental challenge with updating, sometimes referred to as "unlearning," is that it is impossible to prove that a memory will never return (Clem & Schiller, 2016). Instead, one can only show that a memory was not recovered at a given time point, without guaranteeing that it will not reappear later. Conversely, the reappearance of a memory—recovery from updating or intrusion at a later test—does not necessarily support the hypothesis of interference. Memory recovery could result from incomplete disruption of the original memory trace (Clem & Schiller, 2016; Lee et al., 2017), with only the targeted associations being affected, while other components, such as environmental visual details or general procedural aspects, are preserved (Hardt et al., 2009).

Reconsolidation and interference are not necessarily mutually exclusive processes; rather, they may coexist and interact to influence memory dynamics (Clem & Schiller, 2016). We propose that this interaction may serve as a mechanism underlying the memory intrusions observed in our study. Specifically, when participants learned Script 2, Script 1 memories were likely reactivated, initiating reconsolidation. During this process, some Script 1 memories could be updated both quantitatively (e.g., modifying specific object pair associations) and qualitatively (e.g., altering the strength of original memories). However, portions of Script 1 memories that were not sufficiently updated or weakened during this process may persist. These residual memories could coexist with the new Script 2 memories and potentially compete with them, contributing to the observed memory interference.

In addition to reconsolidation and interference accounts, other theoretical frameworks may, at first glance, seem capable of explaining the intrusion effects observed in our study. In what follows, we discuss four of these frameworks, assessing the extent to which they account for the observed intrusion pattern. The frameworks are as follows: (a) fuzzy-trace theory, (b) the source-monitoring framework (Johnson et al., 1993) and similarly the activation-monitoring framework (Roediger et al., 2001), (c) a state-dependency hypothesis (Gisquet-Verrier et al., 2015; Millin et al., 2001), and (d) memory integration theory (Gisquet-Verrier & Riccio, 2018).

Fuzzy-trace theory proposes that memory traces are encoded as both verbatim details and gist representations (Reyna & Brainerd, 1995). Over time, verbatim traces fade while gist traces remain more stable, leading recollection to rely on these abstracted representations. In this view, our intrusion pattern could reflect a shift from detailed to gist-based memory. Rather than relying primarily on the specific object features and box–location details from each script, participants may have leant on gist knowledge that "both changed." This gist-based retrieval could bias them toward selecting a changed object together with a changed box, even if only some of the original details are retained. While both a gist-based account and our reconsolidation-interference interpretation could plausibly explain some aspects of the intrusion pattern, the gist-based account makes a prediction that does not fit our data. Gist-based choices of box location should reflect reliance on coarse spatial information rather than precise object–box associations, but as Figure 4 shows, in the six repeated objects condition, participants chose the Script 2 location significantly more often than any of the control locations. This result shows that they had at least some detailed information about the box locations. Brain activity patterns might also help differentiate the two accounts. Previous neuroimaging work links gist-based retrieval and false memories to activity in semantic processing regions, such as the middle temporal gyrus (Webb et al., 2016). Therefore, intrusion-related activity that preferentially engages these semantic networks would be more consistent with a gist-based mechanism than with one driven by reconsolidation or interference.

The source-monitoring framework (Johnson et al., 1993) suggests that intrusions arise when people misattribute the internal versus external source of remembered content. Along similar lines, the activation-monitoring framework (Roediger et al., 2001) emphasizes that semantically related items tend to be coactivated during learning, increasing the likelihood of source confusion. On these views, encoding Script 2 may have reactivated Script 1, producing overlapping internal and external memory evidence that renders attribution to the correct episode difficult. Because the object pairs in the two scripts were exemplars from the same semantic category, their representations were more likely to be coactivated and thus more difficult to keep separate. Related work demonstrates that presenting same-category items together impairs location memory (Lu et al., 2024), likely because semantic similarity increases competition among items at retrieval (Xue et al., 2025). More broadly, semantic similarity may make related representations less distinct and harder to discriminate, providing a possible parallel to our intrusion effects. However, although this account can explain intrusions of individual elements, it does not fully account for the linked intrusion pattern, in which both the object and the box intrude together as a pair.

Beyond these frameworks, the state-dependency hypothesis suggests that manipulations introduced immediately after memory reactivation can alter the participant's internal state, which then becomes associated with the reactivated memory trace (Gisquet-Verrier et al., 2015; Millin et al., 2001). Can this hypothesis account for our results? During the later retrieval phase in our paradigm, the absence of cues corresponding to the altered internal state induced by the new learning in our study produces a mismatch between the conditions present during reactivation and those at testing, thereby impairing retrieval of the original memory (Gisquet-Verrier & Riccio, 2018; Gisquet-Verrier et al., 2015; Lee et al., 2017; Nader & Hardt, 2009). This effect predominates after weak learning (Gisquet-Verrier & Riccio, 2018), however, and is therefore unlikely to explain the results we observed under strong training conditions.

A fourth approach, memory integration theory, proposes that reactivated memories can transiently incorporate new information through rapid neuronal reorganization independent of protein synthesis (Gisquet-Verrier & Riccio, 2018). Whether the intrusion effects we observed reflect protein synthesis-dependent reconsolidation—the interpretation we favor—or the rapid network-level integration proposed by memory integration theory remains to be determined.

Summary

In sum, this study demonstrates the flexibility of script-like action sequences, showing that the susceptibility to intrusions of components and sequences from Script 2 into Script 1 is significantly influenced by the type of action performed when learning the scripts and the similarity between two learned scripts. Unlike what is known about other memory forms, modification of these script-like action sequence memories engages linked sequence changes, offering a unique perspective on how memory adapts in real-world contexts—modifications occur in smaller sequences, where individual elements are altered together, rather than in isolation.

Constraints on Generality

We acknowledge several limitations of this study. First, to maintain experimental control, our paradigm utilized minimal, artificial sequences. While this successfully captured interactions between linked steps, future work is needed to determine whether these principles extend to the cascading modifications characteristic of longer, goal-directed scripts in naturalistic settings.

Second, the actions we utilized were restricted to clicking and dragging due to the limitations inherent in computer interfaces. Future research incorporating real-time physiological signal measurements in naturalistic scenarios could provide a more detailed understanding of how different actions contribute to the modification of various scripts. Another limitation of this study is that the sample consists entirely of undergraduate students. However, given that memory is a fundamental cognitive function, we believe our results are applicable to the adult population, particularly young adults. Nevertheless, as plasticity in brain systems changes with age, further research is necessary to assess the generalizability of our findings to older adults.

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