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BRIEF REPORT

Agency as a Bridge to Form Associative Memories

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The perception of agency can influence memory when individuals feel their decisions exert control over their environment. While perceived agency has been shown to increase memory for items, most real-life situations are much more complex. Here, we examined how an individual's agency to influence the outcome of a situation affects their ability to learn associations between items that occur prior to and after a decision is made. In our paradigm, participants were told they were playing a game show where they had to help a trial unique cue, a "contestant," choose between three doors. On "agency" trials, participants were allowed to pick any door they wanted. On "forced-choice" trials, participants were instructed to select a door that was highlighted. They then saw the outcome, a "prize" that was behind the selected door. Across multiple studies, we find evidence for agency-related memory enhancements for contestants, a pattern that extended to contestant-prize, contestant-door, and door-prize associations. Additionally, we found that agency benefits for inferred cue-outcome relationships (i.e., door-prize) were limited to situations when choices were motivated by an explicit goal. Finally, we found that agency acts indirectly to influence cue-outcome binding by enhancing processes akin to inferential reasoning which associate information across item pairs containing overlapping information. Together, these data suggest having agency over a situation leads to enhanced memory for all items in that situation. This enhanced binding for items may be occurring by the formation of causal links when an individual has agency over their learning environment.

Keywords: associative memory, agency, hippocampus, encoding

Supplemental materials: <https://doi.org/10.1037/xge0001356.sup>

Individuals are motivated to exert agency, such that they feel their choices and actions allow them to influence the external environment around them (Gallagher, 2012; Haggard, 2017; Haggard & Chambon, 2012; Moore, 2016). Studies on causal learning show that as early as infancy humans learn the relations between actions and the outcomes (Kuhn, 2012) and use this knowledge to act as a

successful agent in their environment. Much of the existing literature on agency emphasizes the process of comparing the outcome of one's own actions with their internal predictions of those actions (Haggard, 2008; Haggard et al., 2002; Wolpert et al., 1995) or generally how our action-outcome contingencies match our intentions (Chambon et al., 2014; Haggard, 2017). However, these processes have been limited in their characterizations of the effects of agency on episodic memory (Hon, 2017).

When an individual has agency over a choice, they experience a sequence in which they are cued to choose among a set of actions which subsequently dictate the outcome. Despite the majority of prior episodic memory literature focusing on outcomes, the association between cues, actions, and outcomes underlies the ability to guide future choice. How do individuals learn and remember the associations in a choice-sequence when we have agency? A key factor in exploring the intersection between memory and agency comes through the execution of a choice. Individuals' choices bias representations of outcomes to be internally consistent in long-term memory (Mather et al., 2000), a mechanism theorized to be driven by cortico-striatal interactions (Delgado, 2007; Leotti & Delgado, 2011; Leotti et al., 2010). Similarly, decision contexts modulate hippocampal memory via striatal and dopaminergic interaction to signal motivational significance (Shohamy & Adcock, 2010). Relevant to our current studies, motivationally relevant studies can enhance the binding of cues with outcomes; however, these studies have not manipulated individual's agency in their decision environment

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We have no conflicts of interest to disclose.

Nicholas Ruiz served as lead for data curation, fanalysis, investigation, software. Vishnu P. Murty served as lead for conceptualization, funding acquisition, supervision. Nicholas Ruiz and Vishnu P. Murty contributed to writing—original draft, writing—review and editing equally.

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(Rouhani & Niv, 2021). Yet, prior work suggests that many of these associative binding processes may actually reflect the act of making a choice, rather than reward motivation. For example, reward signaling in the striatum is present in choice situations but absent in nonchoice situations (Tricomi et al., 2004). We propose that engagement of these motivated memory systems support memories for sequences of action–outcome contingencies and provide a scaffold to associate details within a decision sequence when an individual has agency over the choice.

In line with these predictions, allowing individuals the opportunity to make a choice that influences their learning environment enhances item memory (Gureckis & Markant, 2012; Markant et al., 2016). If time is limited, individuals learn items more effectively when they choose what to study and those choices are honored (Kornell & Metcalfe, 2006). Control over learning environments has also been shown to improve learning and memory even when the choices being made are not directly related to the content of the to-be-learned items. For example, when given exploratory control over a learning environment, participants benefited from being able to control when a certain stimulus–location combination was presented (Voss, Gonsalves, et al., 2011). However, this mechanism was partially driven by the ability to revisit and re-study previously seen items (Voss, Warren, et al., 2011). Prior work from our group has divorced active control and learning from stimulus timing, order, content, and presentation of the to-be-remembered items. In a series of studies, participants were given a choice to click on one of two “cards” which would reveal a to-be-learned item. The cards were unrelated to the revealed items and did not control where or when the item would appear. Given this simple choice, Murty et al. (2015, 2019) found participants better-remembered items that appeared as a result of participants choice compared to when they were forced to overturn one of the cards. While the existing literature shows how agency over a choice can positively affect memory for the outcome of a choice, it does not shed much light onto memory for the overall decision sequence, thus precluding the ability to understand how perceived choice influences associative memory processes more akin to event memory.

We hypothesize giving individuals agency over a similar decision sequence will boost associative memory for the elements embedded within a decision sequence. This idea is consistent with existing hippocampal theories of associative learning as well as its role in binding multiple elements of an experience (Eichenbaum et al., 2007; Mayes et al., 2007; Squire et al., 2004). In order to support adaptive memory formation, the binding of action to outcome only occurs when the action is voluntary and deliberate, as these represent states when internal predictions match with sensory outcomes (Ebert & Wegner, 2010; Frith, 2014; Haggard et al., 2002; Moore & Obhi, 2012). However, little work has been done evaluating how this binding may be expanded to the domain of memory. Work that has explored this effect either test memory for the item that is acted upon (Hon & Yeo, 2021) or the outcome of the action (Murty et al., 2015, 2019) but not for the associations between items. We predict agency will enhance the associative binding of cues and outcomes in memory. There are two possible ways in which this might occur. We predict that agency could enhance memory for the component parts of the sequential chain, allowing for greater inferential binding between items in overlapping pairs (Zeithamova & Preston, 2010) and thus greater cue–outcome binding.

Across three studies, we aim to explore how agency over a choice–sequence will affect associative memory for the components of the sequence, and further delineate the nature of agency on this underlying representation. Participants are told they are participating in a game show, where they will have to help a trial-unique contestant choose between one of three doors which reveals a prize. Critically, participants will either get to choose any of the three doors freely, “agency” trials, or they will be forced to select a door by the experimenter, “forced-choice” trials. We expect agency to act as a bridge, bolstering associative memory for: items that occur prior to a choice, the choice item, and the item that appears as a result of the choice. Further, we ran a series of posthoc analyses to better understand the underlying nature of associative memory representations, delineating whether memory for intermediate pairs of the sequence leads to enhanced cue–outcome binding and how agency can affect this relationship.

Study 1a and 1b

Method

Participants and Design

One hundred seventy-nine participants were recruited across two studies (Study 1a $n = 48$; Study 1b $n = 131$) via Prolific.ac, an online subject pool for behavioral studies (Palan & Schitter, 2018). To qualify for this study, participants must have reported being 18–35 years old, having normal or corrected-to-normal vision, living within the United States, and speaking fluent English. Participants were required to use a desktop or laptop computer, use of mobile devices was restricted. Sample sizes for both studies were determined a priori using a power analysis (Cohen, 1988) with $\alpha = 0.05$ and power = 0.95. We based the sample size of Study 1a on an effect size from a previous study (Murty et al., 2015) which required participants to remember an item based on a choice without testing associative memory. The sample size from Study 1b was based on effect sizes obtained from Study 1a; however, this yielded a much larger sample size suggesting that Study 1a may have been slightly underpowered. Participants’ data were excluded from the final analysis if they did not respond to at least 75% of the encoding trials, 75% of the retrieval trials, made repetitive responses on 50% or more consecutive trials for retrieval phase 2 or retrieval phase 3, or performed below chance on contestant memory retrieval (see “Statistical Analysis”). This resulted in an $n = 42$ for Study 1a and an $n = 98$ for Study 1b. Participants were paid at a rate of \$8–\$10/hr for their participation.

Materials and Procedure

Informed consent and stimuli were presented using Inquisit, an online-based experiment-hosting website (Grootswagers, 2020). Studies 1a and 1b contained the same stimuli and procedures. Study 1b was a pre-registered, replication of Study 1a (AsPredicted #58695). The experimental stimuli consisted of cartoon figures generated within the Toca Boca application (<https://tocaboca.com/apps>), cartoon doors with patterns, and photographs of neutral, man-made objects (e.g., blender). The Toca Boca characters were used in a previous study and all contained neutral facial expressions (Murty et al., 2020). 7 cartoon-patterned doors were created using royalty-free templates from www.vecteezy.com. These

doors were pre-screened in a separate group of participants ($n = 43$) who rated their likeability on a scale from 1 to 5. The three highest rated doors (water pattern [$M = 3.23$, $SD = 1.43$], leaf pattern [$M = 3.62$, $SD = 1.26$], and lego-brick pattern [$M = 2.85$, $SD = 1.40$]) were chosen for the experiment. 197 object images were also pre-screened by the same group of subjects who rated whether they knew what the object was as well as how much they would like to win that object on a game show on a scale from 1 to 5. From this, 120 objects were selected based on at least 80% of the subjects having reported knowing what the object was. From these 120 objects, stimulus lists containing 60 Toca Boca characters and 60 objects were created for both studies, with each list counterbalanced by preference for the items on that list. For Study 1a, six stim lists were created and presented to groups of eight participants. For Study 1b, five stim lists were created and presented to groups of 25–27 participants. All participants completed an incidental encoding gameshow task, a short working memory task, and a retrieval task. Results from the working memory task were not analyzed and will not be reported here, the purpose of this task was to provide filler (average completion time: 5 min) between the encoding and retrieval tasks.

The first segment of the task was the incidental encoding task. The incidental encoding task (Figure 1) consisted of 40 trials and was modeled after a gameshow. Participants were told the first phase of the experiment was a game show. On each trial, they would see a unique “contestant” (Toca Boca character) who would ask for their help in choosing one of three doors (each of which was numbered). Behind each door was a prize, and one of the doors had higher value prizes than the rest. Their job was to help the contestants win the best prize. Critically, they were told the producer may or may

not share their insights with the contestant. Sometimes the producer will ask them to choose a certain door, and when this happens one of the doors will be highlighted in red. Finally, they were told after they make their selection, they will see the door the contestant ultimately selected, and the prize that was behind that door.

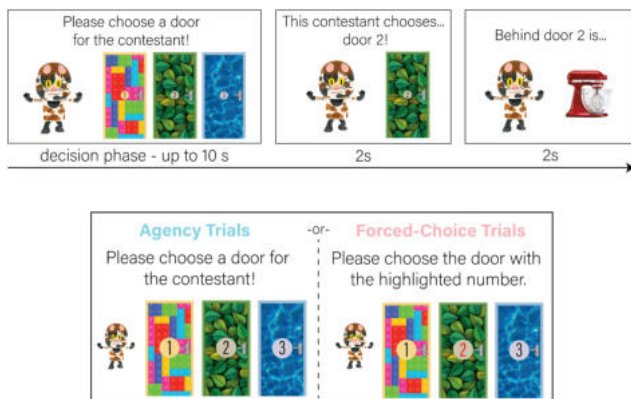
The contestants were trial-unique Toca Boca characters. The three doors remained in the same position for each trial, each subject, and across both studies so spatial location and door identity could not be dissociated. The position of the doors was randomly selected and the doors were numbered. Participants were told some doors lead to better prizes to encourage them to fully explore each door. Unbeknownst to participants, the object image presented was pre-determined by the experimenter in a randomized manner, thus allowing us to manipulate perceived agency rather than actual control over learning. Each trial in the encoding task consisted of a sequence of images. First, participants saw the contestant and the three doors on the screen. They were given 10 s to choose one of the three doors for the contestant. After a choice was made, participants saw the contestant and the chosen door (2 s), and finally, they saw the contestant and the unique prize for that trial (2 s). There was a 2-s intertrial interval and then the next trial began.

There were two types of trials: agency and forced-choice (Figure 1). On agency trials, participants were informed the producer would share their response with the contestant, and to choose any door. On forced-choice trials, participants were told the producer selects the door for this trial and they were instructed to select the door with the highlighted number (the number was changed to red). Participants would make a choice by clicking on the door itself. There were 20 agency trials and 20 forced-choice trials, across eight blocks consisting of five trials each. Each block alternated between agency and forced-choice trials, with the trial type of the first block being counterbalanced across participants.

After the encoding task, participants completed a short working memory task, the visual digit span. This task is provided by Inquisit based on Woods et al. (2011). Data from this task was not analyzed and served only as a filler between the encoding and retrieval tasks.

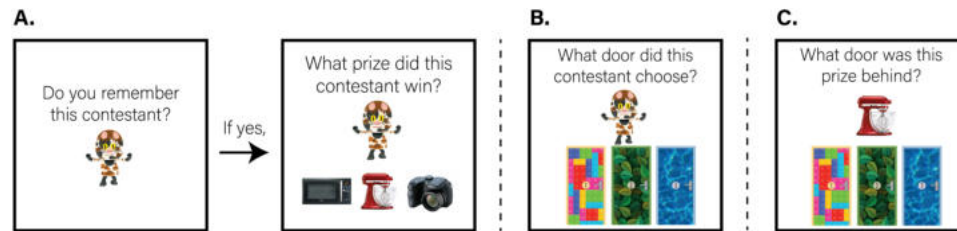
Finally in the last segment after the working memory task, participants completed a surprise retrieval task which consisted of three subphases (Figure 2). The first phase consisted of 60 trials, on each trial participants were presented with either a contestant from the encoding phase or a novel contestant (40 old contestants, 20 new contestants; Figure 2A). They were instructed to indicate whether they remembered the contestant from the encoding task (yes) or not (no). If they responded yes, they were shown three objects from the encoding phase. They were asked to indicate which prize the contestant won. One of the prizes was the correct prize associated with that contestant and the other two prizes were seen in the encoding phase associated with different contestants. The second retrieval test consisted of 40 trials in Study 1a and 60 trials in Study 1b (Figure 2B). Participants were again presented with either old or new contestants and were instructed to indicate which door that contestant chose. The three doors from the encoding phases were presented in the same order as they were during encoding. Study 1a only contained 40 trials due to a programming error, therefore not all old contestants were seen in this phase for participants in Study 1a. On average, in Study 1a participants saw 26.7 old contestants and 13.3 new contestants during this phase. All analyses reflect this difference in presentation number. The third phase of retrieval consisted of 40 trials (40 old prizes; Figure 2C). Participants were

Figure 1
Incidental Encoding Phase for Studies 1a and 1b



Note. Participants were told they were participating in a game show, where they had to help trial-unique contestants select a door. They were told that behind each door was a different type of prize and some doors contained better prizes than others despite object image pairings being pre-determined by the experimenter. At the start of each trial, participants saw the contestant and the three doors. They were either asked to choose any door for the contestant (agency trials) or select the door with the highlighted number (forced-choice trials). They were given up to 10 s to make a choice. After choosing one of the three doors, they viewed the contestant and the door that was selected. Finally, they saw the contestant and the prize that was behind the selected door. See the online article for the color version of this figure.

Figure 2
Retrieval Phases



Note. (A) Contestant recognition and contestant–prize associative memory tests. In a surprise retrieval test, participants were told they would see various characters and were to indicate by making a “yes” or “no” response as to whether they remember seeing that character as a contestant in the game show task. If they responded “yes,” they would then see the same character and three prizes. They were then asked to indicate which prize that character won. The three prizes had all previously been viewed in the encoding phase. (B) Contestant–door associative memory test. Participants were told they would again view various characters who may or may not have been in the game show task. They were instructed to select the door that the character chose during the encoding phase. (C) Prize–door associative memory test. Participants were told they were going to see all of the prizes from the game show task and had to indicate which door that prize was behind. Participants saw the three retrieval phases in the order presented in this figure. See the online article for the color version of this figure.

presented with each of the 40 prizes from the encoding task and were instructed to indicate which door that prize was behind. Each of the retrieval tasks was self-paced, with a maximum response time of 10 s.

Finally, participants completed the Intolerance of Uncertainty Scale (IUS; Freeston et al., 1994), to test an auxiliary hypothesis whether there was a relationship between anxiety associated with uncertainty and memory performance on a task requiring a choice to be made. This questionnaire was not included in subsequent studies. After completion of this questionnaire, individuals were paid for their time.

Statistical Analysis

In addition to the exclusion criteria listed above, we conducted a quality check on the data to ensure performance was above chance. To do this, we calculated corrected recognition scores (hit rate minus false alarm rate) for contestant memory regardless of which condition (agency or forced-choice) the item appeared in. This provided a general score for cue memory. Participants whose corrected recognition was below zero, indicating they did not perform above chance, were excluded from further analysis.

To examine deliberation differences during the decision phase of the encoding task, reaction time was first analyzed on a between-subjects level. During encoding, participants were given up to 10 s to make a choice between one of the three doors or selected a highlighted door. We excluded any trials in which the participant did not make a response during the decision phase as these trials were given a reaction time of 10 s. While it is possible individuals were using this time to study the items on the screen, we cannot infer anything from a nonresponse trial and thus they were removed from further analysis. Then, mean reaction times were calculated for each condition and compared using *t*-tests. For all analyses using *t*-tests, reported *p* values are two-tailed, with values <.05 considered statistically significant. 95% confidence intervals are reported where appropriate. Effect sizes (Cohen *d* for *t*-tests, η^2 for ANOVA) were calculated using the “effectsize” and “lsr” packages in R (v 0.4.5).

Below, we describe the summary statistics we generated for each individual participant for each of our three retrieval tasks. We first examined contestant recognition memory using corrected recognition across conditions. Contestant–prize, contestant–door, and door–prize memory was calculated using accuracy. For all analyses, data were compared across conditions using paired *t*-tests.

Next, we ran a series of control analyses. First, we examined if differences in reaction times across conditions influenced subsequent memory. To do this, we used generalized linear mixed-effects models to examine the relationship between response times and memory outcome. These models were implemented using the lme4 package in R (lme4 v 1.1-26; R v 4.0.3), using a model comparison approach where we determined how the addition of another factor influenced the overall model fit for each of our four memory tests. As we predict condition (agency, forced-choice) will be the strongest predictor of memory outcome, we first created a baseline model which predicts memory outcome by condition (memory ~ condition + [1|subject]). This baseline model was compared to a reaction time model which predicts memory outcome by condition and reaction time (during the decision phase; memory ~ condition + rt + [1|subject]). The reaction time model was subsequently compared to an interaction model which predicted memory outcome by condition, reaction time, and the interaction between condition and reaction time (memory ~ condition × rt + [1|subject]). Finally, where applicable, the reaction time model was compared to a reaction time only model (memory predicted by only reaction time: memory ~ rt + [1|subject]). All models were computed on a trial-wise level and included “subject” as a random effect to account for within-subjects variation in the data. We used analysis of variance (ANOVA) to conduct model comparisons. Data from studies 1a and 1b were combined for this analysis.

We next were interested in whether a preference bias during the decision phase may have influenced memory outcome performance. Choice preference across the two studies was assessed using a χ^2 test. Specifically, we compared participants’ idiosyncratic preferences in selecting each of the three doors against 1/3rd for each door. Next, we examined if any subject-level bias had an influence on

memory performance. If a participant preferred one of the three doors, and therefore had a response bias toward that door during the agency decision phase, this would cause an inflated baseline or “chance” level performance during retrieval phases two (contestant–door memory) and three (prize–door memory). To correct this, we employed a permutation-based bootstrapping procedure. First, each participant’s associative memory responses were shuffled and accuracy was recalculated for agency and forced-choice trials. A difference score (agency minus forced-choice) was then calculated. Then a group average was calculated across participant’s difference scores, generating “group chance” performance. This was repeated 10,000 times for both retrieval phases. Finally, p -values were calculated by determining the probability of the mean accuracy of actual group performance according to the “group chance” distribution.

We additionally examined the relationship between IUS scores and memory performance. Statistical analyses and results of this data can be found in the online supplemental materials. Briefly, data were collapsed across Studies 1a and 1b and there was no correlation between IUS score and memory performance on any of the recall phases.

Finally, we were interested in examining whether having agency over the decision sequence was leading participants to view the items as a sequence of interconnected events rather than sets of individual associative pairs (see Figure 4A–C). To probe this, we examined how performance of contestant (A)–door (B) and door (B)–prize (C) corresponded to performance of contestant (A)–prize (C). While the A–B (contestant–door) and A–C (contestant–prize) pairs were seen together during the encoding phase, the B–C (door–prize) pair was never seen together. If participants viewed the sequence as individual items of A, B, and C, successful retrieval of the A–C pair could be influenced by successfully retrieving the first item A (cue), its relationship with item B (choice item), then recalling B’s relationship with item C (outcome). Whereas remembering the pairs as unitized, relational pairs would indicate participants could successfully recall the A–C pair without needing to recall A–B or B–C. To examine this relationship, we utilized a generalized linear model with a binomial distribution predicting A–C performance with a two (condition: agency, forced-choice) by three (sequence performance) model examining the main effect of condition and sequence performance as well as their interaction. We operationalized sequence performance as a three-factor variable (Figure 4A) including 0 (neither A–B nor B–C were correctly recalled), 1 (either A–B or B–C were correctly recalled), or 2 (both A–B and B–C were correctly recalled). We predict a condition by sequence performance interaction such that items seen in the agency condition are better remembered, leading to enhanced binding of A–C pairs. However, it would still be unclear how exactly agency is affecting cue–outcome (A–C) binding. It is possible that agency is providing a novel mechanism that directly affects the binding of cues and outcomes. A second hypothesis is that agency is indirectly affecting cue–outcome binding by way of enhancing memory for the intermediate pairs (A–B and B–C). To examine the true nature of how agency affects cue–outcome binding, we conducted a mediation analysis using the “lavaan” package in R (Rosseel, 2012). We estimated an indirect effect model via 5,000 iterations of nonparametric bootstrapping. As the factors in the mediation model were controlled manipulations within the experiment, as well as experienced in temporal order (A is shown before B, which is shown before C), we should be able to draw definite

conclusions about whether agency acts directly on cue–outcome binding or if its relationship is mediated by sequence performance. For these exploratory analyses, we collapsed data across Studies 1a and 1b to increase statistical power.

Data Availability

Stimuli, experimental code, analysis code, and data for all three studies can be found at: <https://osf.io/ek53n/>.

Results

Analysis of Decision Phase

We first examined whether agency leads to differences in reaction times during the decision phase. Across both studies, reaction times were faster in the forced-choice condition versus the agency condition; Study 1a: forced-choice, $M = 2,062$ ms, $SD = 553$ ms; agency, $M = 2,429$ ms, $SD = 813$ ms; $t(41) = 3.72$, $p < .001$; Study 1b: forced-choice, $M = 2,184$ ms, $SD = 677$ ms; agency, $M = 2,405$ ms, $SD = 913$; $t(97) = 3.03$, $p = .003$.

We next examined whether there was a response bias in the decision phase at the group level and if any bias could partially explain any memory difference. Our analysis first examined the frequency at which each of the three doors was chosen across all participants, where we found no significant difference in the amount of times a door was chosen compared to chance in either study; Study 1a: $\chi^2(4) = 1.14$, $p = .89$; Study 1b: $\chi^2(4) = 1.23$, $p = .87$.

Contestant Memory

Memory for each contestant was probed in the first phase of retrieval (Figure 2A) using corrected recognition (hits minus false alarms; see Table 1 for M s and SD s). Memory was above chance in both conditions for both Study 1a, t 's(41) > 8.42 , p 's $< .001$, and Study 1b, t 's(97) > 13.40 , p 's $< .001$. We next compared corrected recognition across conditions (Figure 3A). Across studies, corrected recognition was enhanced for contestants from the agency condition versus those in the forced-choice condition; Study 1a: $t(41) = 4.92$, $p < .001$, $d = 0.77$; Study 1b: $t(97) = 5.73$, $p < .001$, $d = 0.57$.

Associative Memory

As part of phase 1, contestant–prize associative memory (accuracy) was probed if the participants reported remembering the contestant (Figure 2A). Memory for contestant–prize pairs was above chance (chance = 1/3rd) for both agency and forced-choice pairs in Study 1a, agency: $t(40) = 3.51$, $p = .001$; forced-choice: $t(41) = 3.55$, $p < .001$, and in Study 1b; agency: $t(97) = 7.78$, $p < .001$; forced-choice: $t(96) = 3.49$, $p < .001$. In Study 1a, there was no difference in memory for contestant–prize associative memory for pairs associated with the agency condition versus pairs associated with the forced-choice condition, $t(40) = 0.18$, $p = .86$, $d = -0.02$; Figure 3B. With increased sample size, Study 1b showed enhanced memory for contestant–prize pairs when those pairs occurred in the agency condition versus pairs from the forced-choice condition, $t(96) = 3.24$, $p = .002$, $d = 0.43$ (Figure 3B).

In the second phase of retrieval, contestant–door associative memory (accuracy) was probed (Figure 2B). Memory for

Table 1

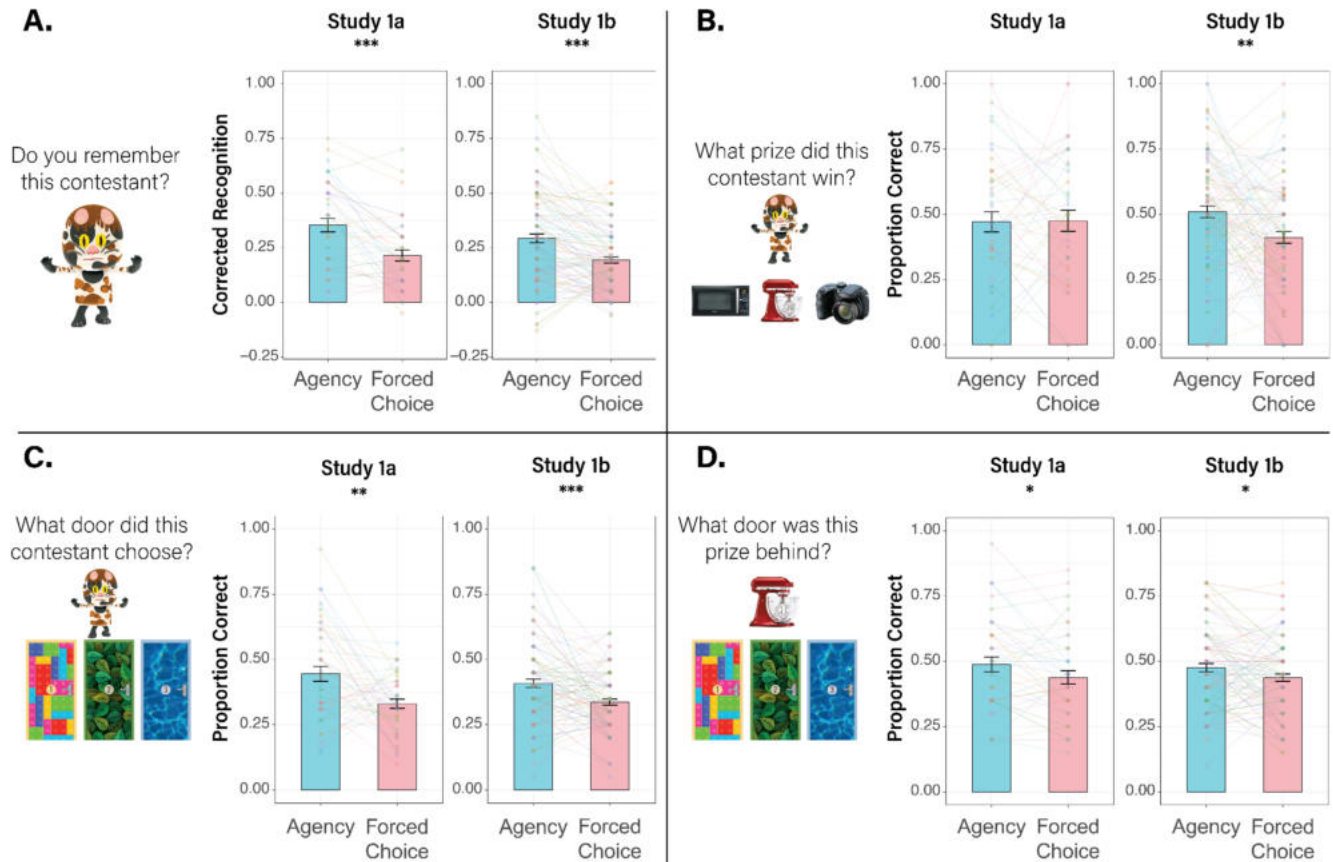
Mean (and Standard Deviation) Scores for All Memory Tests Across Agency and Forced-Choice Trials for Study 1a and 1b

Memory test	Study 1a		Study 1b	
	Agency	Forced-choice	Agency	Forced-choice
Contestant hit rate	0.49 (0.20)	0.36 (0.18)	0.44 (0.19)	0.34 (0.17)
Contestant false alarm rate	0.14 (0.11)		0.15 (0.13)	
Contestant corrected recognition	0.35 (0.20)	0.21 (0.16)	0.29 (0.20)	0.19 (0.14)
Contestant–prize accuracy	0.47 (0.25)	0.48 (0.26)	0.51 (0.22)	0.41 (0.22)
Contestant–door accuracy	0.44 (0.18)	0.33 (0.11)	0.41 (0.16)	0.34 (0.11)
Prize–door accuracy	0.49 (0.18)	0.44 (0.17)	0.48 (0.16)	0.44 (0.14)

contestant–door pairs was above chance (chance = 1/3rd) for agency pairs, $t(41) = 3.91$, $p < .001$, but not forced-choice pairs, $t(41) = -0.18$, $p = .86$, in Study 1a and in Study 1b; agency: $t(97) = 4.63$, $p < .001$; forced-choice: $t(97) = 0.34$, $p = .73$. In Study 1a, participants better-remembered the contestant–door associative pair if the pair occurred in the agency versus forced-choice condition, $t(41) = 3.22$, $p = .003$, $d = 0.75$ (Figure 3C). This result was replicated in Study 1b where memory for contestant–door associative pairs from the agency condition was enhanced compared to pairs in the forced-choice condition, $t(97) = 3.72$, $p < .001$, $d = 0.51$; Figure 3C. We next ran a permutation-based bootstrapping analysis to control for the influence of any subject-level response bias during the decision phase on memory. After shuffling responses on the contest–door retrieval phase and recalculating an accuracy difference score on the subject level, we obtained a group chance mean. The p -value obtained by parametric bootstrapping is $< .001$

Figure 3

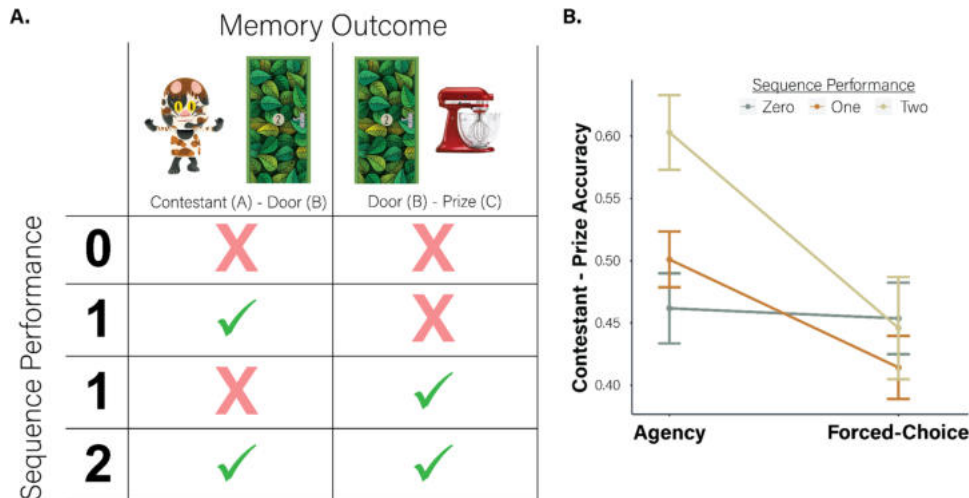
Retrieval Results for Studies 1a and 1b



Note. (A) Contestant corrected recognition. Across Study 1a and 1b, there was a significant difference in corrected recognition between contestants viewed in agency trials versus contestants viewed in forced-choice trials. (B) Contestant–prize associative memory accuracy. For Study 1a, there was no statistically significant difference across contestant–prize associative pairs that occurred in agency trials versus forced-choice trials. For Study 1b, contestant–prize associative pairs that occurred in agency trials had statistically higher accuracy than pairs that occurred in forced-choice trials. (C) Contestant–door associative memory accuracy. Across both studies, contestant–door associative pairs that occurred in agency trials had significantly higher accuracy than pairs that occurred in forced-choice trials. (D) Prize–door associative memory accuracy. Across both studies, prize–door associative pairs that occurred in agency trials had significantly higher accuracy than those that occurred in forced-choice trials. Individual dots represent each participant. Error bars indicate SEM. See the online article for the color version of this figure.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 4
Sequence Performance on Cue–Outcome Binding for Study 1



Note. To investigate the mechanism by which agency was influencing cue–outcome binding, we conducted a generalized linear model with a binomial distribution predicting contestant A–prize C performance with a 2 (condition: agency, forced-choice) by 3 (sequence performance) model. (A) Sequence Performance. Sequence performance was operationalized as a three-factor variable within the model quantifying the number of intervening pairs (contestant A–door B and door B–prize C) correctly recalled in a given sequence. “0” indicates neither A–B nor B–C were recalled. “1” can indicate either A–B or B–C was recalled. “2” indicates both A–B and B–C were recalled. (B) A–C accuracy by Condition and Sequence Performance. We found a significant condition by sequence performance interaction such that participants were more likely to recall A–C if they remembered more of the intervening pairs and they had agency over the sequence. See the online article for the color version of this figure.

revealing none of the 10,000 group chance means had an absolute value higher than the actual group level mean of 0.08.

The final phase of retrieval probed associative memory for door–prize associations (Figure 2C). Memory for door–prize pairs was above chance (chance = 1/3rd) for both agency and forced-choice pairs in Study 1a, agency: $t(41) = 5.50, p < .001$; forced-choice: $t(41) = 4.09, p < .001$, and in Study 1b; agency: $t(97) = 9.00, p < .001$; forced-choice: $t(97) = 7.24, p < .001$. For Study 1a, participants better-remembered pairs from the agency condition versus pairs from the forced-choice condition; $t(41) = 2.22, p = .03, d = 0.29$ (Figure 3D). This result was replicated in Study 1b, where memory for agency pairs was enhanced compared to forced-choice pairs, $t(97) = 2.22, p = .03, d = 0.26$ (Figure 3D). A permutation-based bootstrapping analysis was conducted to explore whether a subject-level response bias during the decision phase influenced memory between conditions. After shuffling responses on the door–prize retrieval phase and recalculating an accuracy difference score on the subject level, we obtained a group chance mean. The p -value obtained by parametric bootstrapping is .002 revealing 18 of the 10,000 group chance means had an absolute value higher than the actual group level mean of 0.04.

Control Analysis for Reaction Time Differences Across Conditions

The above results show enhanced items and associative memory when the participants had agency over the decision sequence versus when they were forced to choose. However, the memory results may have been confounded with differences in reaction time occurring

during encoding. To determine if differences in memory across condition result from reaction time, we characterized how predictive reaction time and condition were of memory outcome for contestant recognition, and associative memory. The results of these analyses are discussed in full in the online supplemental materials. Briefly, the reaction time model provided a better model fit than the baseline model for contestant recognition and contestant–prize associative memory but not for contestant–door or prize–door associative memory. For contestant recognition and contestant–prize associative memory, condition remained a significant predictor of memory and additional data provided below (see Study 3) lead us to the conclusion reaction time during the encoding phase was not the sole mechanism driving memory differences across condition.

Analysis of the Underlying Representation of Associative Memories

The results thus far suggest that agency increases pairwise associative memory. However, these prior analyses do not discriminate whether agency enhances memory separately for each individual associative pair, or rather whether agency enhances the binding of all the associations into one integrated sequence through an inferential reasoning process. If agency facilitates memory integration, there should be inter-dependence among memory measures, such that successful contestant–prize (A–C) memory would depend on successfully recalling the intermediate pairs, contestant–door (A–B) and door–prize memory (B–C). If either one or both of the constant–door (A–B) or door–prize (B–C) were not successfully recalled, then one may be unable to recall the contestant–prize (A–C) pair. To examine whether

binding of contestant (A)–prize (C) memory is enhanced by inferring their relationship via overlapping information from the other pairs of the decision sequence (contestant A–door B, door B–prize C), we conducted a 2 (condition: agency, forced choice) \times 3 (sequence performance: 0 if neither A–B nor B–C was recalled, 1 if either A–B or B–C was recalled, or 2 if both A–B and B–C were recalled) analysis of variance on A–C memory (Figure 4A). We did not find a significant main effect of condition, $\beta(1, 905) = -0.04, p = .81, 95\% \text{ CI} [-0.33, 0.02], SE = 0.15, z = 0.24$. We did find a significant main effect of sequence performance, $\beta(1, 905) = 0.27, p = .002, [0.10, 0.44], SE = 0.09, z = 3.05$, such that, when more intermediate pairs recalled, participants were more likely to recall the A–C pair. Critically, we found a significant condition by sequence outcome interaction, $\beta(1, 905) = -0.32, p = .02, [-0.58, -0.06], SE = 0.12, z = -2.37$, such that memory for the A–C (contestant–prize) pair was enhanced when more of the sequence was also remembered (Figure 4B). This effect was particularly higher when the participants had agency over the sequence compared to when they did not (forced trials), suggesting that agency may be increasing A–C memory by increasing memory for the intermediate pairs.

However, to fully understand the relationship between agency and cue–outcome binding, we conducted a follow-up mediation analysis to test whether agency is providing a novel mechanism to directly enhance binding. Condition was independently associated with enhanced A–C memory ($\beta = 0.075, p = .001, 95\% \text{ CI} [0.03, 0.12], SE = 0.02, z = 3.31$) and with enhanced sequence performance ($\beta = 0.14, p < .001, [0.08, 0.21], SE = 0.03, z = 4.28$). Sequence performance was also independently associated with enhanced A–C memory ($\beta = 0.04, p = .02, [0.01, 0.07], SE = 0.02, z = 2.32$). Finally, we did find evidence for sequence performance mediating the relationship between A–C memory and condition (indirect effect: $\beta = 0.01, p = .045, [0.001, 0.01], SE = 0.01, z = 2.00$). This suggests agency is enhancing A–C memory indirectly by way of enhancing memory for the intervening pairs within the sequence.

Study 1: Discussion

Here, we provide evidence that the sense of agency enhances memory for items associated with a choice, and facilitates the formation of associations between items, choices, and outcomes. Further, we show evidence that agency may enhance binding by bolstering memory for intervening pairs containing overlapping information. Together we show that imbuing individuals with agency during learning with a choice benefits memory for items proximal to that choice and facilitates the binding of the items into an integrated sequence.

There were a few limitations in this set of studies, mainly centered on a lack of specification on the role of overarching goal states and the independence of the presentation of stimuli, which we address in two follow-up experiments. Study 2 addresses whether agency needs to act in concert with goal states to provide memory enhancements. Study 3 utilizes a slightly modified version of the game show task to pursue a purer test of whether the agency is providing the bridge for a chaining mechanism to occur.

Study 2

Overview

Study 2 was designed to address the limitation that the choices made in Study 1 served a more complex function than simply

exerting control. Study 1 found agency enhances memory cues, choices, outcomes, and the associations between these items. This expanded upon previous work from our group has found positive memory effects from agency in complete absence of any reward or goal state (Murty et al., 2015, 2019). However, while we manipulated the ability to make a choice or not, we also layered a goal state on top of the choice via the instructions to help each contestant find the best prize. This critical manipulation is making the choice to pick a door more complex than simply exerting control. We must consider that participants may be making a choice within the value-based goal of searching for the highest value prizes. Despite the fact that the prize order presentation was controlled, Study 1 cannot completely disentangle the simple act of making a choice from the possibility participants may have also been performing a higher order task of accomplishing a reward-related goal. To fully understand the effects of agency, we need to understand the boundary conditions on how it may affect memory. More simply stated, does one need a goal to see an associative memory benefit of choice. Models of motivation propose control over actions that are most effective when they adaptively work toward accomplishing goals rather than simply performing actions in isolation (Anderson & Milson, 1989; Shohamy & Adcock, 2010). In prior work, when these two things are in competition, goals overshadow agency (Katzman & Hartley, 2020). It is possible that stripping the choice of the underlying goal may break the mechanism seen in the current study, if agency is most useful when it subserves goal-directed actions. This would provide valuable insight as to the amount of control needed to find agency-related associative memory enhancements.

To address this, we modified the game show task's instructions to remove any reference to finding the highest value prize. Instead, participants were instructed their goal was to remember which contestants won which prizes. By removing the possibility one might need to resolve a higher level function or value-based goal, Study 2 allows for the direct testing of whether agency-related memory enhancements only occur when the ability to exert control serves a utility. If the ability to exert control alone can influence memory in absence of a goal-state, we expect that memory to be enhanced for items and item-pairs experienced in the agency condition compared to those in the forced-choice. However, if exerting control only impacts memory when that action subserves a goal, we would expect to see less of an effect of agency on memory for items and item-pairs in this study.

Method

Participants and Design

Two hundred fifty-three participants were recruited via Prolific.ac. The inclusion criteria were the same as Study 1. The sample size for this study was determined a priori based on a power analysis using the interaction term from a model combining data from Studies 1a and 1b, predicting A–C memory by condition and sequence performance (A–C memory \sim condition*sequence performance, see section “Analysis of the Underlying Representation of Associative Memories” in Study 1). We used the “mixedpower” package in R, which revealed a required sample size of $n = 204$ to achieve a power = 0.8 with $\alpha = 0.05$. While power was lower in this study compared to Studies 1a and 1b, the required sample size for power = 0.95 was $n = 350$ and thus too large to reasonably recruit. Adjusting for

participant dropout, we recruited 10 batches of roughly 25 subjects each over the course of 7 days. Data were only collected on weekdays, with data collection beginning around 9 am EST and concluding by 9 pm EST to keep data collection within relatively normal working hours (Crump et al., 2013). The exclusion criteria also remained the same from Study 1.

Materials and Procedure

The same stimuli set was used from Study 1. For Study 2, 10 stim lists were created and shown to groups of 25–26 participants at a time. The procedure was identical to Study 1 with the following exception. The instructions for the encoding phase were modified to exclude any reference finding the best prize or implication that some doors lead to better prizes. Instead, participants were told their task was to remember which contestant received which prize. The rest of the procedure remained the same as Study 1 (Figures 1 and 2).

Statistical Analysis

All of the statistical analyses for Study 2 were identical to Study 1, see above (“Statistical Analysis”) for more details.

Results

Analysis of Decision Phase

We first examined whether agency leads to differences in reaction times during the decision phase. Reaction times were faster in the forced-choice condition versus the agency condition; forced-choice, $M = 2,540$ ms, $SD = 790$ ms; agency, $M = 2,788$ ms, $SD = 959$ ms; $t(204) = 5.21$, $p < .001$.

We next examined whether there was a response bias in the decision phase at the group level and if any bias could partially explain any memory difference. Our analysis first examined the frequency at which each of the three doors was chosen across all participants, where we found no significant difference in the amount of times a door was chosen compared to chance, $\chi^2(4) = 1.49$, $p = .83$.

Contestant Memory

Memory for each contestant was probed in the first phase of retrieval (Figure 2A) using corrected recognition (hits minus false alarms; see Table 2 for means and standard deviations). Memory was above chance for both conditions, t 's(204) > 21.90 , p 's $< .001$. We next compared corrected recognition across conditions (Figure 5A). Corrected recognition was enhanced for contestants from the agency condition versus those in the forced-choice condition, $t(204) = 7.43$, $p < .001$, $d = 0.34$.

Associative Memory

As part of phase 1, contestant–prize associative memory (accuracy) was probed if the participants reported remembering the contestant (Figure 2A). Memory for contestant–prize pairs was above chance (chance = 1/3rd) for both agency and forced-choice pairs; agency: t 's(203) = 18.88, p 's < 0.001 ; forced-choice: t 's(203) = 14.62, p 's $< .001$. Different from Study 1, there was no difference in memory for contestant–prize associative memory for pairs associated with the agency condition versus pairs associated with the forced-choice condition, $t(202) = 1.00$, $p = .32$, $d = .09$ (Figure 5B).

Table 2

Mean (and Standard Deviation) Scores for All Memory Tests Across Agency and Forced-Choice Trials for Study 2

Memory test	Study 2	
	Agency	Forced-choice
Contestant hit rate	0.61 (0.21)	0.52 (0.22)
Contestant false alarm rate	0.14 (0.14)	
Contestant corrected recognition	0.47 (0.25)	0.38 (0.25)
Contestant–prize accuracy	0.60 (0.20)	0.58 (0.24)
Contestant–door accuracy	0.45 (0.18)	0.35 (0.11)
Prize–door accuracy	0.39 (0.14)	0.37 (0.13)

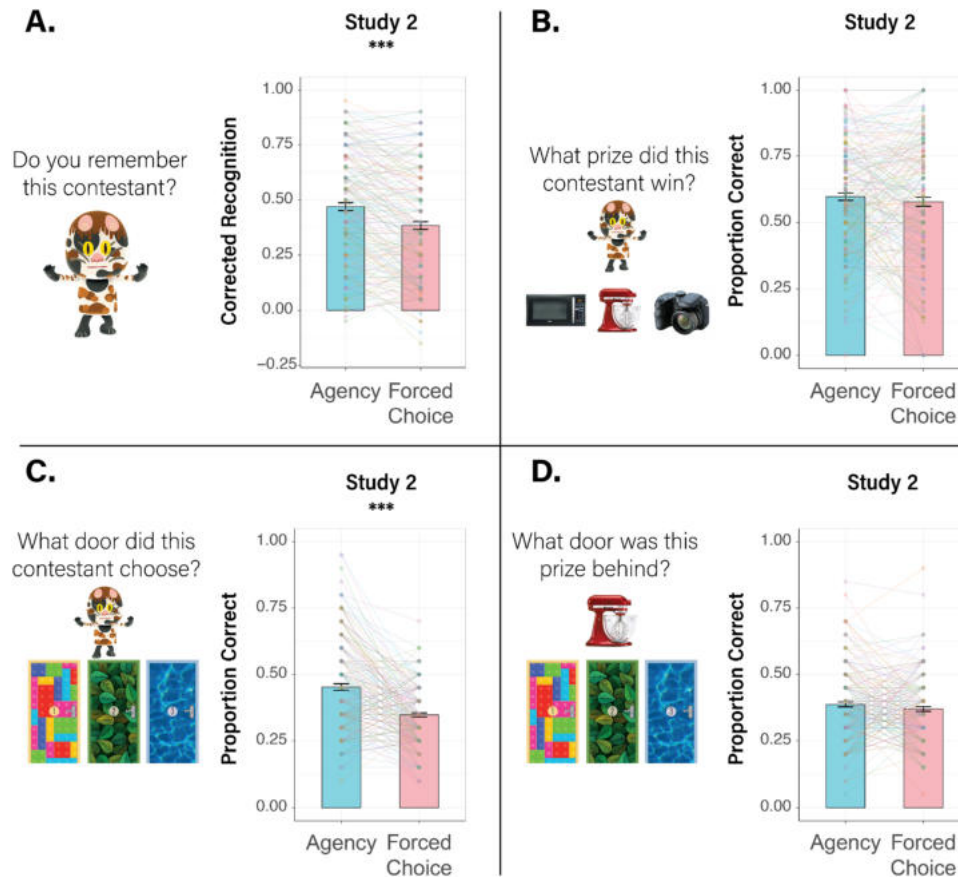
In the second phase of retrieval, contestant–door associative memory (accuracy) was probed (Figure 2B). Memory for contestant–door pairs was above chance (chance = 1/3rd) for agency pairs, $t(204) = 9.69$, $p < .001$, but not forced-choice pairs, $t(204) = 1.86$, $p = .06$. Participants better-remembered the contestant–door associative pair if the pair occurred in the agency versus forced-choice condition; $t(204) = 7.98$, $p < .001$, $d = 0.71$ (Figure 5C). We next ran a permutation-based bootstrapping analysis to control for the influence of any subject-level response bias during the decision phase on memory. After shuffling responses on the contest-door retrieval phase and recalculating an accuracy difference score on the subject level, we obtained a group chance mean. The p -value obtained by parametric bootstrapping is $< .001$ revealing none of the 10,000 group chance means had an absolute value higher than the actual group level mean of 0.10.

The final phase of retrieval probed associative memory for door–prize associations (Figure 2C). Memory for door–prize pairs was above chance (chance = 1/3rd) for both agency and forced-choice pairs; agency: $t(204) = 5.67$, $p < .001$; forced-choice: $t(204) = 4.18$, $p < .001$. Again, unlike Study 1, there was no significant difference in memory of pairs from the agency condition versus pairs from the forced-choice condition, $t(204) = 1.42$, $p = .16$, $d = 0.13$ (Figure 5D). A permutation-based bootstrapping analysis was conducted to explore whether a subject-level response bias during the decision phase influenced memory between conditions. After shuffling responses on the door–prize retrieval phase and recalculating an accuracy difference score on the subject level, we obtained a group chance mean. The p -value obtained by parametric bootstrapping is .16 revealing 1,613 of the 10,000 group chance means had an absolute value higher than the actual group level mean of 0.02.

Control Analysis for Reaction Time Across Condition

Some of the above results show enhanced item and associative memory when participants had agency over the decision sequence versus when they did not. However, the memory results may have been confounded by differences in reaction time occurring during encoding. To determine if differences in memory across condition result from reaction time, we characterized how predictive reaction time and condition were of memory outcome for contestant recognition and associative memory. The results of these analyses are discussed in full in the online supplemental materials. Briefly, the reaction time model provided a better model fit than the baseline model for contestant recognition and contestant–prize associative memory but not for contestant–door or prize–door associative

Figure 5
Retrieval Results for Study 2



Note. (A) Contestant corrected recognition. There was a significant difference in corrected recognition between contestants viewed in agency trials versus contestants viewed in forced-choice trials. (B) Contestant–prize associative memory accuracy. There was no statistically significant difference across contestant–prize associative pairs that occurred in agency trials versus forced-choice trials. (C) Contestant–door associative memory accuracy. Contestant–door associative pairs that occurred in agency trials had significantly higher accuracy than pairs that occurred in forced-choice trials. (D) Prize–door associative memory accuracy. There was no significant difference in accuracy for prize–door associative pairs across condition. Individual dots represent each participant. Error bars indicate SEM. See the online article for the color version of this figure.
* $p < .05$. ** $p < .01$. *** $p < .001$.

memory. For contestant recognition and contestant–prize associative memory, condition remained a significant predictor of memory and additional data provided below (see Study 3) lead us to the conclusion reaction time during the encoding phase was not the sole mechanism driving memory differences across condition.

Analysis of the Underlying Representation of Associative Memories

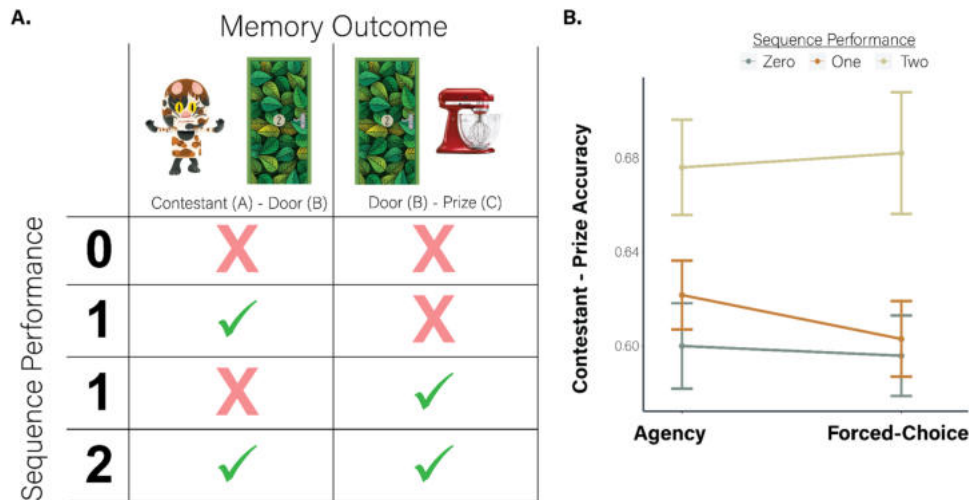
While Study 2 did not see the same pattern of associative memory results as Study 1, we were still interested in exploring whether there was a relationship between cue–outcome binding with condition and recall of the intervening pairs (Figure 6). Using the same model as in Study 1, we did not find a significant effect of condition, $\beta(4, 420) = -0.03$, $p = .77$, 95% CI $[-0.23, 0.17]$, $SE = 0.10$, $z = -0.29$. We did find a significant effect of sequence performance,

$\beta(4, 420) = 0.16$, $p = .01$, $[0.04, 0.29]$, $SE = 0.06$, $z = 2.53$, such that the more successful participants were at recalling the A–B and B–C pairs, the more likely they were to recall the A–C pair. Finally, we did not see a significant interaction between condition and sequence performance, $\beta(19, 442, 005) = -0.03$, $p = .77$, $[-0.21, 0.16]$, $SE = 0.09$, $z = -0.30$. As we did not see an effect of condition on A–C associative memory, no mediation analysis was conducted for this study.

Study 2: Discussion

In Study 2, we made adjustments to our task to explore how goals and control over actions interact to enforce the role of agency in memory. In particular, Study 2 removed instructions which could have been guiding participants to accomplishing a value-based goal. Instead, they were simply told to remember which contestants

Figure 6
Sequence Performance on Cue–Outcome Binding for Study 2



Note. To investigate the mechanism by which agency was influencing cue–outcome binding, we conducted a generalized linear model with a binomial distribution predicting contestant A–prize C performance with a 2 (condition: agency, forced-choice) by 3 (sequence performance) model. (A) Sequence Performance. Sequence performance was operationalized as a three-factor variable within the model quantifying the number of intervening pairs (contestant A–door B and door B–prize C) correctly recalled in a given sequence. “0” indicates neither A–B nor B–C were recalled. “1” can indicate either A–B or B–C was recalled. “2” indicates both A–B and B–C were recalled. (B) A–C accuracy by Condition and Sequence Performance. We found a significant main effect of sequence performance such that participants were more likely to recall A–C if they remembered more of the intervening pairs. Unlike Study 1, we did not find a condition by sequence performance interaction. See the online article for the color version of this figure.

won which prizes. Study 2 provides evidence that the sense of agency enhances memory for items associated with a choice, but has less of an effect on associative memory between cues and outcomes, as well as other pairwise associations.

We predicted that having control over one’s actions may only serve utility if that action is working toward completing a goal. Indeed, in Study 1 when there was a top-down goal to find the door with the best prize, we see an agency-related memory enhancement on cues and other pairwise associations. This effect did not carry over into Study 2 when the value-based goal was removed. Previous work has shown agency-related memory enhancements only when the ability to perform an action had a high level of utility (Katzman & Hartley, 2020). The combinations of Study 1 and Study 2 support a more nuanced picture of how goal states influence memory in the context of agency. Namely, we show that an overarching goal state is not necessary for memory of choice cues nor the relationship between choice cues and decisions, but is critical for the ability to bind the entire choice sequence (i.e., cue–outcome memory). These findings suggest to extend associative memory to cues and their outcomes, the outcomes may have to be salient. This still leaves open the boundary conditions of what types of goals facilitate cue–outcome binding, and we only explored the space of value-based goals. However, in related work from our laboratory, which albeit only explores outcome memory rather than cue–outcome binding, we have found memory enhancements when the utility of the outcome is ambiguous (Murty et al., 2015, 2019) or when uncertainty about cue–outcome relationships is moderate as opposed to random or fully expected (Shen et al., 2022).

Study 3

Overview

Study 3 was designed to address a limitation on how agency may enhance binding of cues and outcomes via a chaining process. Study 1 found evidence that cue–outcome (A–C) binding was indirectly modulated by agency with memory for intervening pairs containing overlapping information mediating this effect. It has been shown that inferential processes can bind information across a sequence when the pairs of items contain overlapping information (Zeithamova & Preston, 2010). While the effect seen in Study 1 may have been driven by an inferential process, the fact that individuals directly experienced the A–C pair provides another mechanism by which participants may instead rely on an episodic memory of that exposure. To resolve this, we modified the game show task to only show one item on the screen at a time. In this way, participants will not be able to use episodic memory to recall a specific item-pair exposure and will instead need to rely on inferential processing if a binding mechanism is involved in integrating the sequence in memory. Study 3 also uses the same instructions as Study 1, given the results of Study 2 show agency-related memory modulation occurs when the actions performed with agency serve a goal.

Method

Participants and Design

Two hundred forty-four participants were recruited via Prolific.ac. The inclusion criteria remained the same as Study 1. The sample

size was determined a priori based on the same power analysis used in Study 2. Adjusting for participant dropout, we recruited nine batches of roughly 27 subjects each over the course of 7 days. Data were only collected on weekdays, with data collection beginning around 9 am EST and concluding by 9 pm EST to keep data collection within relatively normal working hours (Crump et al., 2013). The exclusion criteria also remained the same as Study 1.

Materials and Procedure

The same stimuli set was used from Study 1. For Study 3, nine stim lists were created and shown to groups of 26–28 participants at a time. The general procedure for Study 3 was the same as Study 1 in that participants completed an incidental encoding phase, a short working memory task, and a surprise retrieval test.

The incidental encoding task contained the same instructions and general design as Study 1. The key difference was Study 3 presented items individually (Figure 7). Participants would first see the contestant (2 s), followed by the decision phase (up to 10 s) where they were instructed to either freely choose a door (agency trial) or select the highlighted door (forced-choice trial), after a selection was made the selected door would be presented alone (2 s), and finally they would see a unique prize for that trial (2 s). There was a 2 s inter-trial interval and the next trial would begin.

Participants in Study 3 completed the same working memory task as Study 1. The final phase was a surprise retrieval task which remained the same as Study 1.

Statistical Analysis

All of the statistical analyses for Study 3 were identical to Study 1.

Results

Analysis of Decision Phase

We first examined whether agency leads to differences in reaction times during the decision phase. Reaction times were faster in the forced-choice condition versus the agency condition; forced-choice,

$M = 1,920$ ms, $SD = 521$ ms; agency, $M = 2,024$ ms, $SD = 648$ ms; $t(198) = 2.69$, $p = .008$.

We next examined whether there was a response bias in the decision phase at the group level and if any bias could partially explain any memory difference. Our analysis first examined the frequency at which each of the three doors was chosen across all participants, where we found no significant difference in the amount of times a door was chosen compared to chance, $\chi^2(4) = 1.03$, $p = .91$.

Contestant Memory

Memory for each contestant was probed in the first phase of retrieval (Figure 2A) using corrected recognition (hits minus false alarms; see Table 3 for means and standard deviations). Memory was above chance for both conditions, t 's(198) > 20.10, p 's < .001. We next compared corrected recognition across conditions (Figure 8A). Corrected recognition was enhanced for contestants from the agency condition versus those in the forced-choice condition, $t(198) = 7.40$, $p < .001$, $d = 0.51$.

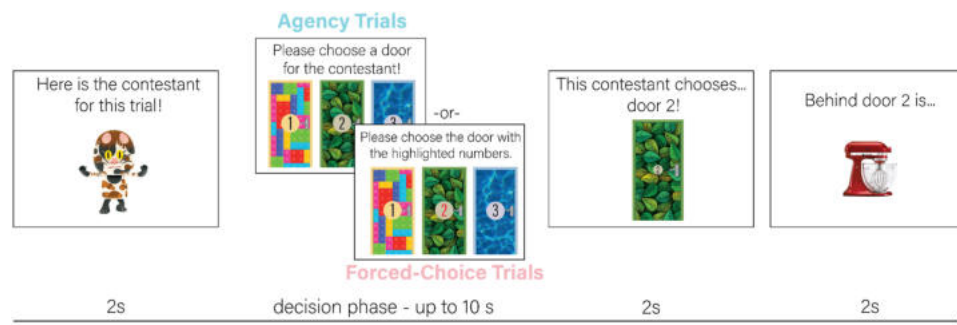
Associative Memory

As part of phase 1, contestant–prize associative memory (accuracy) was probed if the participants reported remembering the contestant (Figure 2A). Memory for contestant–prize pairs was above chance (chance = 1/3rd) for both agency and forced-choice pairs; agency: $t(198) = 8.83$, $p < .001$; forced-choice: $t(197) = 5.95$, $p < .001$. There was a significant difference in memory for contestant–prize associative memory for pairs associated with the agency condition versus pairs associated with the forced-choice condition; $t(197) = 2.09$, $p = .04$, $d = 0.23$; Figure 8B.

In the second phase of retrieval, contestant–door associative memory (accuracy) was probed (Figure 2B). Memory for contestant–door pairs was above chance (chance = 1/3rd) for agency pairs, $t(198) = 7.10$, $p < .001$, but not forced-choice pairs; $t(198) = 1.01$, $p = .31$. Participants better-remembered the contestant–door associative pair if the pair occurred in the agency versus forced-choice condition; $t(198) = 5.40$, $p < .001$, $d = 0.51$ (Figure 8C). We next ran a permutation-based bootstrapping analysis to control for the influence of any subject-level response bias

Figure 7

Modified Game Show Task for Study 3



Note. Task instructions and general design were identical to Study 1 with the following exception: items within the sequence were shown separately rather than paired with another item. In this way, we can more directly test how individuals associate items within the sequence. The retrieval phase remained unchanged (see Figure 2). See the online article for the color version of this figure.

Table 3
Mean (and Standard Deviation) Scores for All Memory Tests Across Agency and Forced-Choice Trials for Study 3

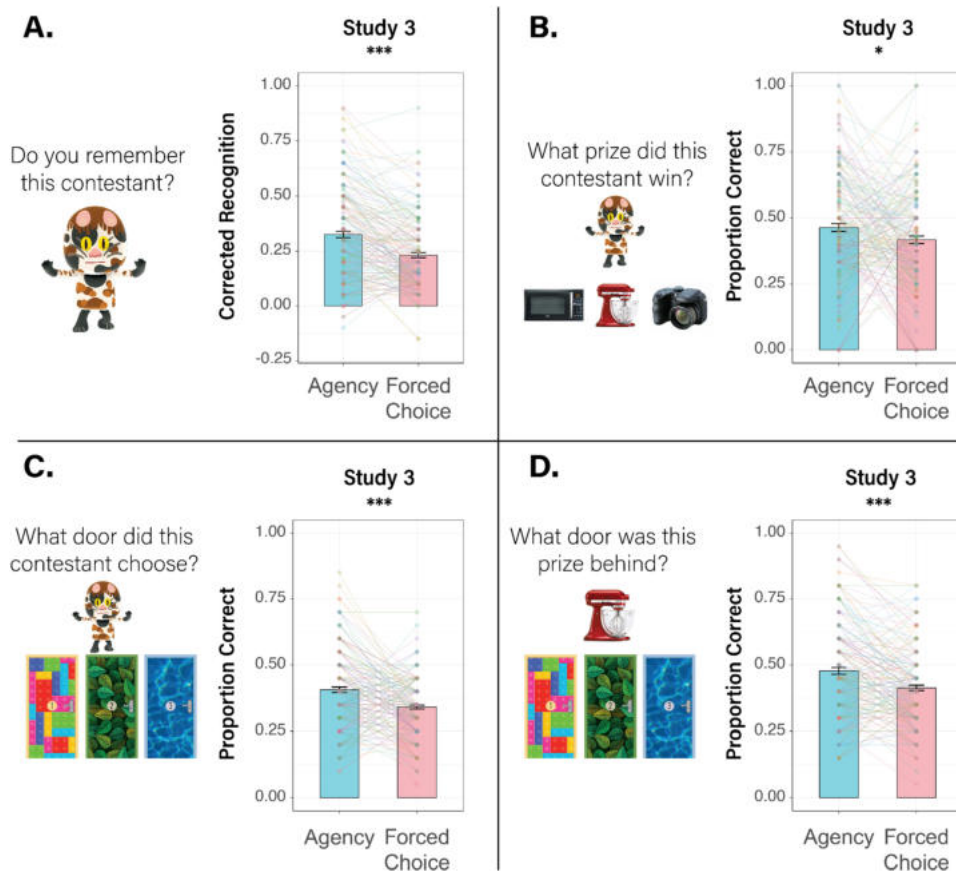
Memory test	Study 3	
	Agency	Forced-choice
Contestant hit rate	0.49 (0.21)	0.39 (0.18)
Contestant false alarm rate	0.16 (0.14)	
Contestant corrected recognition	0.33 (0.21)	0.23 (0.16)
Contestant–prize accuracy	0.46 (0.21)	0.42 (0.20)
Contestant–door accuracy	0.41 (0.14)	0.34 (0.11)
Prize–door accuracy	0.48 (0.18)	0.41 (0.14)

during the decision phase on memory. After shuffling responses on the contest-door retrieval phase and recalculating an accuracy difference score on the subject level, we obtained a group chance mean. The *p*-value obtained by parametric bootstrapping is $<.001$

revealing none of the 10,000 group chance means had an absolute value higher than the actual group level mean of 0.07.

The final phase of retrieval probed associative memory for door–prize associations (Figure 2C). Memory for door–prize pairs was above chance (chance = 1/3rd) for both agency and forced-choice pairs; agency: $t(198) = 11.28, p < .001$; forced-choice: $t(198) = 7.96, p < .001$. There was a significant difference in memory of pairs from the agency condition versus pairs from the forced-choice condition, $t(198) = 5.24, p < .001, d = 0.40$ (Figure 8D). A permutation-based bootstrapping analysis was conducted to explore whether a subject-level response bias during the decision phase influenced memory between conditions. After shuffling responses on the door–prize retrieval phase and recalculating an accuracy difference score on the subject level, we obtained a group chance mean. The *p*-value obtained by parametric bootstrapping is $<.001$ revealing none of the 10,000 group chance means had an absolute value higher than the actual group level mean of 0.06.

Figure 8
Retrieval Results for Study 3



Note. (A) Contestant corrected recognition. There was a significant difference in corrected recognition between contestants viewed in agency trials versus contestants viewed in forced-choice trials. (B) Contestant–prize associative memory accuracy. Contestant–prize associative pairs that occurred in agency trials had statistically higher accuracy than pairs that occurred in forced-choice trials. (C) Contestant–door associative memory accuracy. Contestant–door associative pairs that occurred in agency trials had significantly higher accuracy than pairs that occurred in forced-choice trials. (D) Prize–door associative memory accuracy. Prize–door associative pairs that occurred in agency trials had significantly higher accuracy than those that occurred in forced-choice trials. Individual dots represent each participant. Error bars indicate SEM. See the online article for the color version of this figure.
 * $p < .05$. ** $p < .01$. *** $p < .001$.

Control Analysis for Reaction Time Across Condition

Some of the above results show enhanced item and associative memory when participants had agency over the decision sequence versus when they did not. While there was no difference in reaction time during the decision phase, we were still interested in examining whether reaction time may have been a predictor of memory. To test this, we characterized how predictive reaction time and condition were of memory outcome for contestant recognition and associative memory. The results of these analyses are discussed in full in the online supplemental materials. Briefly, the reaction time model provided a better model fit than the baseline model for contestant-prize associative memory but not for contestant recognition, contestant-door, or prize-door associative memory. For contestant-prize associative memory, condition remained a significant predictor of memory. However, given the changes made in this study where neither contestant nor prize presentation was modulated by reaction time during the decision phase (where only the door was seen), we conclude reaction time during the encoding phase was not driving memory differences across conditions.

Analysis of the Underlying Representation of Associative Memories

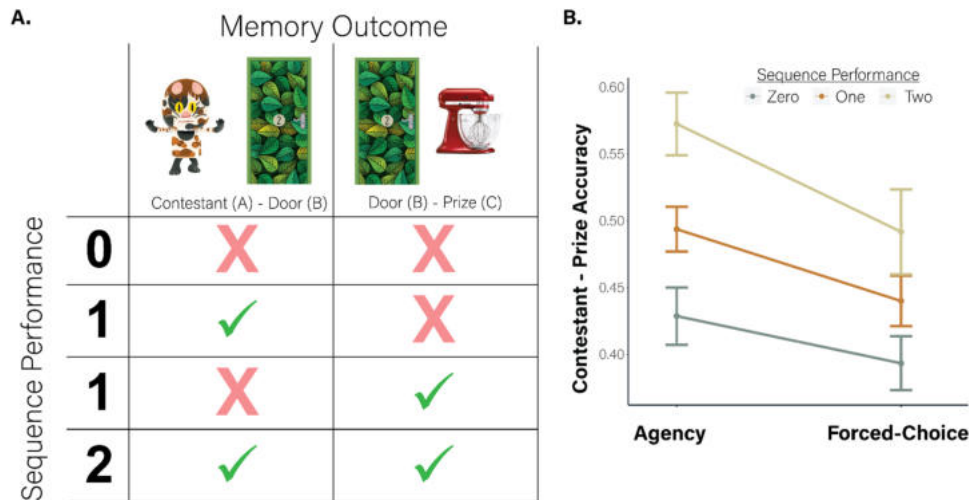
While Study 2 did not see the same pattern of associative memory results as Study 1, we were still interested in exploring whether there was a relationship between cue-outcome binding with condition and recall of the intervening pairs (Figure 9). Using the same model as in Study 1, we did not find a significant effect of condition, $\beta(3,$

$400) = -0.16, p = .16, 95\% \text{ CI } [-0.38, 0.06], SE = 0.11, z = -1.40$. We did find a significant effect of sequence performance, $\beta(3, 400) = 0.28, p < .001, [0.15, 0.41], SE = 0.07, z = 4.11$, such that the more successful participants were at recalling the A-B and B-C pairs, the more likely they were to recall the A-C pair. Finally, we did not see a significant interaction between condition and sequence performance, $\beta(3, 400) = -0.09, p = .39, [-0.29, 0.11], SE = 0.10, z = -0.85$, suggesting the main predictor of A-C memory was recalling more of the intervening pairs in the sequence. However, as we did find an effect of condition on A-C associative memory, we sought to fully understand the relationship between agency and cue-outcome binding. Using the same mediation model as Study 1, we again found Condition was independently associated with enhanced A-C memory ($\beta = 0.05, p = .002, [0.02, 0.09], SE = 0.02, z = 3.06$) and with enhanced sequence performance ($\beta = 0.18, p < .001, [0.13, 0.22], SE = 0.02, z = 7.18$). Sequence performance was also independently associated with enhanced A-C memory ($\beta = 0.06, p < .001, [0.04, 0.09], SE = 0.01, z = 5.25$). Finally, we did find evidence for sequence performance mediating the relationship between A-C memory and condition (indirect effect: $\beta = 0.01, p < .001, [0.03, 0.10], SE = 0.003, z = 4.20$). This suggests agency is enhancing A-C memory indirectly by way of enhancing memory for the intervening pairs within the sequence.

Study 3: Discussion

In Study 3, we made adjustments to the game show task to allow for a purer test of whether agency can enhance the chaining of items

Figure 9
Sequence Performance on Cue–Outcome Binding for Study 3



Note. To investigate the mechanism by which agency was influencing cue-outcome binding, we conducted a generalized linear model with a binomial distribution predicting contestant A-prize C performance with a 2 (condition: agency, forced-choice) by 3 (sequence performance) model. (A) Sequence Performance. Sequence performance was operationalized as a three-factor variable within the model quantifying the number of intervening pairs (contestant A-door B and door B-prize C) correctly recalled in a given sequence. “0” indicates neither A-B nor B-C were recalled. “1” can indicate either A-B or B-C was recalled. “2” indicates both A-B and B-C were recalled. (B) A-C accuracy by Condition and Sequence Performance. We found a significant main effect of sequence performance such that participants were more likely to recall A-C if they remembered more of the intervening pairs. Unlike Study 1, we did not find a condition by sequence performance interaction. See the online article for the color version of this figure.

in a sequence via an inferential reasoning process. Specifically, we adjusted the design to only include one image on the screen at a time, encouraging associative binding. Study 3 provides evidence that agency can enhance memory for items that appear in anticipation of a choice, as well as pairwise associations between cues, choice items, and outcomes. Furthermore, we show evidence that agency enhances memory for all pairwise associations, providing the building blocks for an inferential reasoning mechanism where overlapping information is used to enhance the binding of cues and outcomes. Taken together with the previous studies, we show evidence for agency-related memory enhancements when an individual is given a choice within a sequence. The results seen in Study 3 help contextualize the results seen in Study 1. In Study 3, we again found agency-related memory enhancements for cues and pairwise associations. Furthermore, we replicated that agency-related enhancements in cue–outcome binding were enhanced as a function of memory for intervening pairs.

General Discussion

In the current experiment, we sought to explore whether imbuing individuals with agency via a choice during an incidentally encoded sequence of items could enhance their memory across the sequence. In three studies, we have shown evidence for agency-related memory effects, particularly when individuals have an overarching goal, such that there were enhancements for items that precede a choice (cue), choice items, outcomes, and the pairwise associations between these items. Additionally, we examined mechanisms by which cue–outcome binding may occur with evidence suggesting it may be driven by memory for pairs with overlapping information. While Study 1 showed this effect was specific for sequence items experienced in the agency condition, aspects of the study design may have allowed for alternate mechanisms to drive binding. Study 3 allowed for a purer test of chaining by showing items individually and found cue–outcome binding was being driven by memory for intervening pairs alone. This suggests agency may contribute to cue–outcome binding by enhancing pre-existing inferential mechanisms.

We have shown manipulating agency can enhance memory for items and item pair associations in a sequence. Giving individuals agency over what information to learn and how much time to spend studying has been shown to enhance learning of facts (Metcalfe, 2002; Metcalfe & Kornell, 2003, 2005). However, the learning effects seen in these prior studies may be due in part to metacognitive processes that probe one’s own knowledge base, leading to choices that effectively manipulate the environment to allow for an optimal learning strategy (Kornell & Metcalfe, 2006). Prior work has separated control over the learning environment and metacognitive processes by allowing individuals to actively control timing and content of stimulus presentation to show learning enhancements (Markant et al., 2014; Voss, Gonsalves, et al., 2011; Voss, Warren, et al., 2011). While effects could be driven by a number of processes that come along with control over learning such as increased coordination of attention, they suggest agency can enhance memory when the choices do not work to resolve metacognitively driven mechanisms. Comparatively, the choices made in the current experiment do not influence factors of the learning environment and are relatively simple while still instilling a sense of control over the sequence that allows for memory enhancements.

Work from our group has established that memory can be enhanced via a choice that does not influence stimulus presentation or content of what is to-be-learned (Murty et al., 2015, 2019). This suggests agency can enhance memory by simply allowing an individual to perform an action during learning. However, the current experiment found agency-related memory effects for associative binding including outcomes only when the choice made served a value-based goal. Notably, prior work has yet to explore the space of how agency influences associative binding of cues and actions with outcomes. However, we can garner some insight by revisiting prior work looking solely at outcome memory, as this likely underlies some of the processes guiding cue–outcome and action–outcome binding. We hypothesize that agency may only facilitate outcome memory when outcomes are salient. Prior work showing agency-related benefits in episodic memory for outcomes may result from moderate ambiguity in the relationship between choice and the content of outcomes. For example, in Murty et al. (2015, 2019), this relationship was left quite ambiguous, with choices being made between unfamiliar, repeating characters and no instructions beyond remembering the item that appeared after a choice was made. Furthermore, previous work has found self-directed probing of novel categories enhances learning (Gureckis & Markant, 2012; Markant & Gureckis, 2010) and is potentially driven by motivational processes working to resolve uncertainty (Markant & Gureckis, 2012a, 2012b). Interestingly, agency-related memory enhancements have an inverted U-shaped relationship with uncertainty such that only moderate (and not low nor high) levels of uncertainty led to memory benefits (Hon & Yeo, 2021; Shen et al., 2022). The choices made in Study 2 of the current experiment had a more apparent relationship with the subsequent items, which may have dampened the salience of outcomes by reducing uncertainty. Instead of acting to resolve uncertainty, the choices in the current experiment needed to serve a similar higher-order function, in this case a value-based goal, to show similar memory enhancements, which parallels prior work examining explicit relationships between value and agency (Katzman & Hartley, 2020). Future work could disentangle the role agency plays in memory and associative memory by manipulating the underlying function the agency-related choices serve, particularly across varying levels of uncertainty regarding the identity of that function.

The explanations detailed above may account for enhanced memory on an item level but do not address how participants are encoding the items into an integrated sequence. Agency is possibly modulating memory to integrate items within a sequence into a unified representation. If this were the case, individuals could use the overlapping information they are presented within the sequence to bind distal items together in memory. For example, in order to remember a specific contestant (cue)–prize (outcome) pair, they would need to bind the intervening pairs: contestant (A)–door (B) and door (B)–prize (C). Study 1 shows evidence that participants better-remembered the A–C pair when they remembered more pairs within the sequence and had agency over that trial. This is in line with previous work showing how overlapping information from a single event can bind into an integrated sequence (Horner et al., 2015), particularly when the learners have the ability to control a minor aspect of their experience (Markant, 2020). In Study 3, we modified our design such that item pairs were never directly experienced during the task, and continued to show that A–C binding results from inference from individual pairs. Specifically, Study 3

found evidence for a role for inferential reasoning in cue–outcome binding, such that a mediation model found an indirect relationship between enhanced A–C binding and agency mediated by memory for the intervening pairs in the sequence. Thus, agency may provide more resources for the inferential reasoning mechanism to take advantage of, by enhancing memory for intervening pairs, leading to more binding of cues and outcomes.

While the above analyses imply agency to be the main factor driving the memory enhancements, the current experiment also reliably found significantly longer reaction times during the decision phase for agency trials compared to forced-choice trials in all three studies. As the design of Study 1 and 2 includes presentation of both the contestant and the door during the decision phase, longer reaction times in the agency condition could yield a potential confound when examining memory for the contestant or the contestant–door association. Importantly, our multilevel analysis approach to account for the effects of RT still shows agency-related memory enhancements when considering trial-by-trial reaction time (see the online supplemental materials). However, given that RT may not directly reflect time spent encoding these items, these controls may not be sufficient to account for RT's role in underlying agency-related memory benefits. Thus, we further addressed this issue in Study 3 where only the doors were seen during the decision phase. Using this paradigm, we still found benefits in associative memory despite neither stimuli being related to RT during choice, as neither of those stimuli were on the screen during the decision phase. In some ways, one may have predicted that A–C memory would get worse in the agency condition because items were more temporally distant than in the forced condition. In some regards, we believe these findings need to be replicated in a paradigm where RT is fixed, however, on the other hand, the RT differences seen across conditions in the current experiment may represent deliberation on the choice that is intrinsically part of agency (Vargas & Lauwereyns, 2021). Thus, future studies that explicitly control for decision RT across conditions may actually be removing one of the key factors underlying agency.

While our results are purely behavioral they provide a theoretical framework to better understand the underlying neural systems. We propose that sequence integration by agency could potentially be caused by modulation of the hippocampus. Agency may endorse the formation of associations due to engagement of mesolimbic dopamine systems underlying the act of choosing (Delgado, 2007; Leotti et al., 2010; Leotti & Delgado, 2011), which are known to modulate hippocampal activity (Lisman & Grace, 2005; Shohamy & Adcock, 2010; Shohamy & Turk-Browne, 2013). Critically, hippocampal engagement is an important factor in binding multiple elements of an experience together and which could be driving the findings reported here (Eichenbaum et al., 2007; Mayes et al., 2007; Squire et al., 2004). It is possible that these mechanisms are involved in integrating the various aspects of the sequence when the participants are given the signal that they will have agency over a given trial.

In conclusion, our findings show enhanced memory for the items and the associations between items when an individual is given agency over the situation. We also show that agency may be facilitating the binding of cues and outcomes by indirectly enhancing memory for intervening pairs containing overlapping information. This process may be dependent on hippocampal modulation by cortico-striatal interactions that come online during the act of choosing. However, further work involving neuroimaging will need to be done to definitively

address these questions. Overall, our results add to a growing literature examining how agency over an item or sequence of items can influence memory and bolster associations between items.

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