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Multiple high-reward items can be prioritized in working memory but with greater vulnerability to interference

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Abstract

Emerging literature indicates that working memory and attention interact in determining what is retained over time, though the nature of this relationship and the impacts on performance across different task contexts remain to be mapped. In the present study, four experiments examined whether participants can prioritize one or more high-reward items within a four-item target array for the purposes of an immediate cued recall task, and the extent to which this mediates the disruptive impact of a postdisplay to-be-ignored suffix. All four experiments indicated that endogenous direction of attention toward high-reward items results in their improved recall. Furthermore, increasing the number of high-reward items from one to three (Experiments 1–3) produces no decline in recall performance for those items, while associating each item in an array with a different reward value results in correspondingly graded levels of recall performance (Experiment 4). These results suggest the ability to exert precise voluntary control in the prioritization of multiple targets. However, in line with recent outcomes drawn from serial visual memory, this endogenously driven focus on high-reward items results in greater susceptibility to exogenous suffix interference, relative to low-reward items. This contrasts with outcomes from cueing paradigms, indicating that different methods of attentional direction may not always result in equivalent outcomes on working memory performance.

Keywords Attention · Visual working memory · Interference · Reward · Suffix

Attention and working memory are closely related and interacting constructs. Direction of attention to stimuli in the environment, or representations already present in working memory, helps to ensure that this information stays accessible over the short term (Griffin & Nobre, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Nobre et al., 2004; Souza & Oberauer, 2016; Vogel, Woodman, & Luck, 2005b) or could even reactivate the previously unattended items that have not been represented in a form of sustained neural activity (Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012; Rose et al., 2016). Similarly, the contents of working memory can influence how attention is directed around the environment (e.g., Awh & Jonides, 2001; Downing, 2000; Hu, Xu, & Hitch, 2011). As working memory is a limited capacity system (Cowan, 2001), it is often helpful to optimize task performance within the constraints of this system by directing attention to a subset of targets (Atkinson, Baddeley, & Allen, 2017) and to ignore task-irrelevant distractors (Allen, Baddeley, & Hitch, 2017). This approach is particularly useful when some items in the visual environment are associated with higher reward values. Such an ability has already been reported in the context of prelearning manipulations, in which certain stimuli are preassociated before the memory experiment with different monetary values (Gong & Li, 2014; Infanti, Hickey, Menghi, & Turatto, 2017; Thomas, FitzGibbon, & Raymond, 2016; Wallis, Stokes, Arnold, & Nobre, 2015). It has recently been extended to more online processing and explored experimentally in a series of studies in which participants were instructed to remember a sequence of visual stimuli, but to prioritize certain items from within this sequence based on associated reward values (Atkinson et al., 2018; Hitch, Hu, Allen, & Baddeley, 2018; Hu, Allen, Baddeley, & Hitch, 2016; Hu, Hitch, Baddeley, Zhang, & Allen, 2014). This work consistently produces improved recall accuracy for prioritized

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items, alongside costs to deprioritized items, indicating that limited resources can be flexibly managed online to optimize task performance.

Our work on prioritization has so far been limited to the use of serially presented items, with certain temporal positions within the sequence associated with higher reward values. As serial and simultaneous visual-working-memory tasks can produce distinct patterns of forgetting (e.g., Allen, Baddeley, & Hitch, 2006; Ricker & Cowan, 2014), it is important to examine whether similar outcomes emerge within arrays containing multiple items that are simultaneously presented: Are participants able to select and prioritize high reward items from within such arrays? The visual environment tends to consist of numerous stimuli that vary in value and goal relevance, so such an ability would seem highly advantageous. Recent work by Siegel and Castel (2018) using an item-location binding task and arrays of 10 items (thus likely exceeding working memory capacity) provides some initial evidence that this is indeed possible. Furthermore, a large body of work now exists demonstrating that attention can be directed to certain items within a simultaneously encountered array through visual cues presented before (precueing) or after (retro cueing) target encoding, with resulting response accuracy and/or latency improvements for these cued items (e.g., Griffin & Nobre, 2003; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Schmidt, Vogel, Woodman, & Luck, 2002; Shimi, Nobre, Astle, & Scerif, 2014; Souza & Oberauer, 2016).

While conceptually similar, the direction of attention via either reward values or visual cues is likely to involve at least some nonoverlapping forms of processing. We have so far assumed that reward-based manipulations (Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014) primarily reflect endogenous control of directed attention; certain items are associated with higher reward values based on their serial position, and participants are encouraged to strategically utilize this points scheme when determining how to allocate their attention across the target items throughout each phase of the trial. Reliable effects of this manipulation are consistently observed even though the reward allocation is not predictive of which item will be tested. Indeed, recent evidence indicates that reward-based prioritization effects appear to emerge independently of changes in predictive validity when these factors are orthogonally manipulated (Atkinson et al., 2018). In contrast, visual cueing studies typically involve a perceptual stimulus that directs attention toward a particular item (e.g., a shape outline in the location of the cued item, or an arrow directing to that location). Although effects of visual cueing and probe frequency have not been orthogonally examined, cueing effects are somewhat dependent on their predictive validity regarding which items are tested at the response phase; if a cue is not predictive as to which target will be tested, then it typically has a reduced impact on performance (e.g., Berryhill, Richmond, Shay, & Olson, 2012; Schmidt et al., 2002). As suggested by Atkinson et al. (2018), it should not be assumed that methods of attentional direction always involve equivalent underlying mechanisms. Examining prioritization within a simultaneous presentation context will be helpful not only in understanding how directing attention around the visual environment benefits working memory but also in enabling direct contrasts with the more established literature on visual cueing.

The present series of experiments not only examined priority effects within simultaneously encountered multi-item arrays but also how such effects might interact with postencoding visual interference, such as a stimulus suffix. The stimulus suffix is a to-be-ignored redundant item presented immediately after presentation of the to-be-remembered items. Although participants are instructed to ignore the suffix, it may nevertheless lead to systematic interference effects. Such effects are well established in the domains of auditory-verbal short-term memory (Crowder & Morton, 1969) and visuospatial memory (Nicholls, Parmentier, Jones, & Tremblay, 2005; Parmentier, Tremblay, & Jones, 2004), and it has been demonstrated that the constituent features and spatial location of a suffix can determine the magnitude of interference effects that are observed, depending on task context (Allen, Castellà, Ueno, Hitch, & Baddeley, 2015; Ueno, Allen, Baddeley, Hitch, & Saito, 2011a; Ueno, Mate, Allen, Hitch, & Baddeley, 2011b). A reliably observed finding in serial visual-memory tasks is that such a to-be-ignored suffix stimulus presented after offset of the final target item and prior to the test phase particularly has an impact on both the most recently encountered item and on the item that is being prioritized (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014). Thus, in contrast to visual cueing research, which shows that cued items are protected from or indifferent to interference (Hollingworth & Maxcey-Richard, 2013; Makovski & Jiang, 2007; Makovski & Pertzov, 2015; Makovski et al., 2008; Matsukura, Luck, & Vecera, 2007; Rerko, Souza, & Oberauer, 2014; Souza, Rerko, & Oberauer, 2016; van Moorselaar, Gunseli, Theeuwes, & Olivers, 2014), the direction of attention to high-reward items appears to increase not only memory accuracy but also vulnerability to retroactive interference. These findings have been interpreted as reflecting the operation of a focus of attention within working memory, containing high-priority items and the most recently encountered input from the environment (Hu et al., 2014). This account should extend to the present simultaneous presentation context and would predict equivalent patterns to emerge when items of varying reward value are followed by an interfering suffix stimulus; thus, if participants are able to strategically prioritize higher value items from within an array and hold them in the focus of attention, these items should then show relatively greater interference from a postencoding suffix, compared with low-reward items.

This series of experiments also addresses the extent to which attention can be strategically directed to more than one item. Within the serial presentation context, we (Hitch et al., 2018) have recently demonstrated that participants are able to show prioritization boosts on two items at a time from within a four-item sequence. Similarly, spatially oriented visual cues can direct attention to more than one item, either in the environment (Awh & Pashler, 2000) or when held in working memory (Heuer & Schubö, 2016; Matsukura & Vecera, 2015). Here, we explore whether reward-based strategic prioritization is apparent for one item (Experiment 1), two items (Experiment 2), or three items (Experiment 3) within a four-item array, whether the magnitude of this effect varies with the number of high-reward items that require prioritization, and how this interacts with suffix interference. The final experiment takes this exploration a step further, providing the first direct examination of whether attention-based prioritization can be graded by degrees, by contrasting recall accuracy for items that vary on a scale of reward values.

Experiment 1

The first experiment in this series examined impacts of reward and suffix interference using the same proportion of high-reward and low-reward values as implemented in the exploration of serial memory by Hu et al. (2016; Hu et al., 2014). Thus, a "1114" reward pattern was implemented, with only one item per trial being assigned a high reward and signifying prioritization. Based on previous work, we expected to observe disruptive effects of a to-be-ignored suffix stimulus (Allen et al., 2015; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). We also predicted improvements in accuracy on the high-reward target relative to low-reward items. Finally, extending previous findings (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014) from serial to a simultaneous memory task, we predicted a larger suffix effect on high-reward relative to low-reward items.

Method

Participants

The sample size for this and subsequent experiments was based on Hu et al. (2014). Sample-size estimation was performed as follows: First, the effect size indicators for the reward (highest reward–lowest reward) by suffix (control–suffix) interaction term were obtained from each of the three experiments in Hu et al. (2014). Next, these indicators were integrated by an internal random-effect meta-analysis (Ueno, Fastrich, & Murayama, 2016), resulting in Cohen's *d* of .719, 95% CI [.443, .996]. Finally, a power analysis with this effect size (sample size = 20, alpha = .05) confirmed power of more than .80 in a paired-participant design.

Twenty undergraduate students (14 females, six males; M_{age} = 20.90 years, *SD* = 1.95) from Nagoya University, Japan, took part in the 45-minute experiment, and were paid (1,000 Japanese yen) or received an hour course credit for their participation. All had normal vision and discrimination ability for the shapes and colors.

Materials

Testing was controlled using an HSP3 (Hot Soup Processor, Version 3) program (http://hsp.tv/). All stimuli were simple shapes subtending a visual angle of 0.75°, presented on a white background. A pool of eight shapes (circle, chevron, triangle, star, arch, cross, diamond, flag) and eight colors (black, red, blue, green, yellow, gray, turquoise, purple) were used to construct the experimental stimuli. Shape test probes involved unfilled black outlines, and color test probes were presented as formless color "blobs" (as in Ueno, Mate, et al., 2011b).

Design and procedure

This experiment followed a 2 × 2 repeated-measures design, with reward (Reward 1; Reward 4), and suffix (no suffix; suffix) as factors. There were 256 trials in total, divided into four blocks of 64 trials, with reward and suffix manipulations implemented pseudorandomly across these trials (see below).

Figure 1 illustrates the flow of a trial. At the beginning of each trial, four numbers were presented at the corners of an invisible square (2.25° × 2.25°) for 1,000 ms with a beep sound. These four numbers indicated the size of the "reward" when the target item from each spatial position was correctly recalled. Thus, the magnitude of each number indicated the degree of attention to be allocated to each target in each position. Following Hu et al. (2014), this experiment implemented a "1114" reward pattern, meaning that on every trial, three targets were allocated a reward of 1 point, and one target (the priority item) was allocated a reward of 4 points. The numbers in each position were randomly selected at every trial with a constraint that the total amount of rewards across the whole experiment was equal for each spatial position. Participants were aware that these points represented entirely notional rewards.

Following a 100-ms blank screen, four to-be-remembered objects were presented for 2,000 ms simultaneously. These items were selected from the experimental pool randomly at every trial without an overlapping feature within a trial. For no-suffix trials, a 1,000-ms blank-screen delay then followed. For suffix trials, a 250-ms blank-screen delay was followed by presentation of an additional colored shape (the suffix), displayed for 250 ms at the center of the screen, and then a

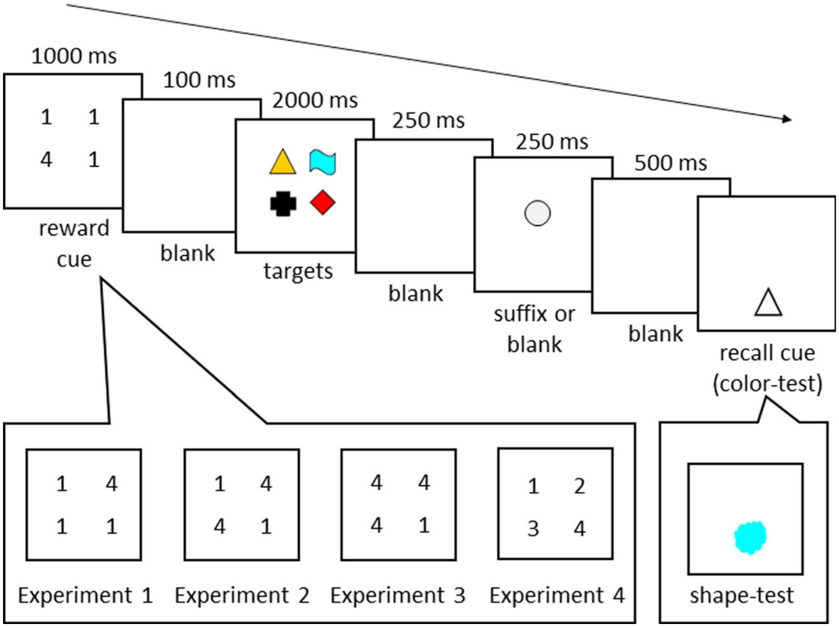

Fig. 1 Schematic illustration of trial procedure in Experiments 1–4

further 500-ms blank-screen delay. The color and the shape of the suffix were randomly selected from the experimental pool without a feature overlap with the targets. No-suffix and suffix trials each made up 50% of the total number of trials and were randomly distributed across the experiment.

In the test phase, a test probe (a color blob or a line drawing of a shape) appeared just below the center of the screen. Participants were required to orally recall the other feature of the probed target object. For example, if the probe was a turquoise blob (see Fig. 1), they had to answer the paired shape (i.e., “flag”). If the probe was a line-drawing of a triangle, they had to answer the paired color. In this case, the correct answer was “yellow.” Even if they were not confident, participants were encouraged to provide their best guess rather than saying “I do not know.” The color-tested trials and shape-tested trials were randomly distributed across the whole experiment (50% chance). The tested target was randomly selected from the four spatial positions with equal probability (25% chance), meaning that point rewards were not predictive of which target would be probed at test (as in Hu et al., 2016; Hu et al., 2014).

Participants were required to repeat the sequence “da, da, da” from a presentation of reward cues until the test probe appeared, to discourage verbal recoding.

Results and discussion

Data in this and all subsequent experiments were analyzed using ANOVA and appropriate follow-up comparisons (Bonferroni–Holm corrected). Performance in shape-probe and color-probe trials was collapsed to provide a single proportion correct measure, for each of the reward levels and suffix conditions, as displayed in Fig. 2. Including the feature-type factor (color or shape) in the ANOVA model indicated that this factor did not interact with any other factor, except for one minor, marginal case in Experiment 2, which was not replicated in any other experiment. Thus, we collapsed these trials in this and subsequent experiments, and provide the descriptive statistics

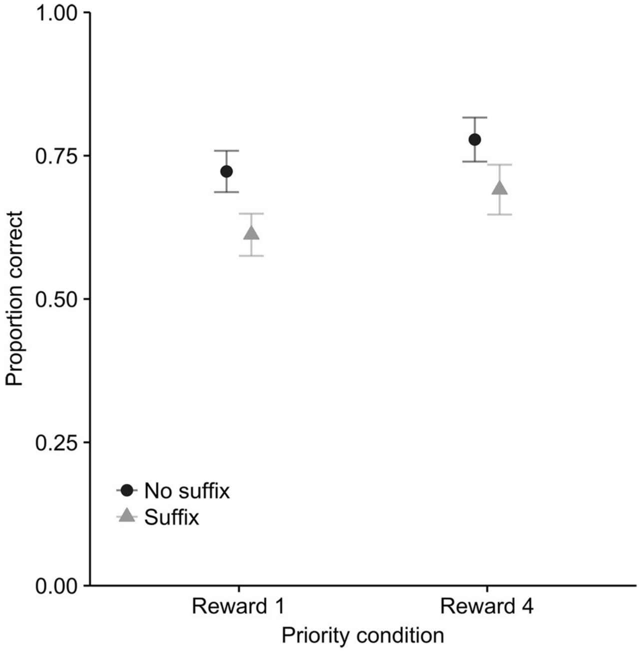

Fig. 2 Proportion correct (error bars show standard error) in Experiment 1

for the separate color and shape trials in the Appendix Tables 1 and 2. Data from all experiments are available on the Open Science Framework (https://osf.io/r96ky/?view_only=53a66b32437048b8930e1c4be94f1af5).

A 2 × 2 ANOVA revealed a significant effect of reward, $F(1, 19) = 5.83$, $MSE = .02$, $p = .026$, $\eta_p^2 = .24$, with recall accuracy higher for Reward 4 ($M = .74$, $SE = .04$) than for Reward 1 ($M = .67$, $SE = .04$). There was also a significant effect of suffix, $F(1, 19) = 32.19$, $MSE = .01$, $p < .001$, $\eta_p^2 = .63$, with performance during no-suffix trials ($M = .75$, $SE = .04$) superior to suffix trials ($M = .65$, $SE = .04$). However, there was no significant interaction between these factors, $F(1, 19) = .61$, $MSE = .01$, $p = .443$, $\eta_p^2 = .03$. Further planned comparisons (Bonferroni–Holm corrected, $p < .05$) revealed suffix effects on both Reward 1 (Cohen's $d = 1.22$) and Reward 4 items ($d = .78$). In contrast. the reward effects in both no-suffix (.45) and suffix (.50) trials were small–medium in size and were not significant (i.e., $p > .05$) after correction for multiple comparisons. The majority of errors involved recall of a feature from another presented item rather than the one probed (i.e., within-list confusion). In this and subsequent studies, there was no specific prediction regarding suffix effects on error types (and no consistent effects were observed), so the data are provided in the Appendix Tables 1 and 2.

Experiment 1 therefore replicated the previously observed positive effects of priority instruction and negative effects of suffix interference (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). Thus, extending from serial to simultaneous presentation for the first time, participants can strategically prioritize an item from within a multitarget array and are vulnerable to interference from a to-be-ignored stimulus presented between target offset and test.

However, the previously consistent observation (using serial presentation) of larger suffix effects for prioritized items was not found in this experiment, and, indeed, the suffix effect size was slightly larger for low-reward items. This would appear to challenge previous assumptions (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014) concerning prioritization and how suffix interference might impinge on this. However, it is possible that simultaneous presentation of multiple targets offers different task affordances to those available in serial memory. Specifically, when exposed to several targets for relatively extended durations (2 s, in the present case), given that any item is equally likely to be tested, participants may be able to focus on the high-reward item, plus at least some of the additional low-reward items on display. This account is supported by the observation of relatively small reward effects overall that did not survive correction for multiple comparison. This ability to prioritize some of the low-reward items within the focus of attention would render them more susceptible to suffix interference and would therefore reduce the probability of observing a Suffix × Reward interaction, particularly as it would not be clear on which low-reward items participants were choosing to focus. Experiment 2, therefore, examined whether such an interaction was observable when more items were identified as being of high reward.

Experiment 2

Hitch et al. (2018) recently demonstrated that, within a sequence of items, participants can strategically prioritize more than one item in response to experimental instruction, with suffix interference then emerging on each prioritized item. Experiment 2 extended this to the processing of simultaneous multi-item arrays, to establish whether similar patterns emerge across presentation contexts. We would expect this to be possible, based on evidence indicating allocation of spatially oriented selective attention to multiple items that are present in the visual environment or being retained in working memory (Awh & Pashler, 2000; Heuer & Schubö, 2016; Matsukura & Vecera, 2015). However, it remains to be seen whether increasing the number of prioritized items results in equivalent overall performance levels and observed boosts, or if capacity or resource limitations means that these are reduced relative to the single-item prioritization condition implemented in Experiment 1.

Furthermore, increasing the number of prioritized items enabled us to check whether the absence of a Reward × Suffix interaction in Experiment 1 simply reflected the tendency of participants to also prioritize some of the low-reward items. If this were the case, increasing the number of high-reward targets (from one to two) provides more experimental control over which items participants are focusing on, and reduces the probability of low-reward items also being prioritized. Thus, for Experiment 2, we expected to observe main effects of reward and suffix, and explored again whether an interaction would be apparent between these factors.

Method

Participants

Twenty undergraduate students (nine females, 11 males; $M_{age} = 19.25$, $SD = 2.02$) from Takachiho University, Japan, took part in the 45-minute experiment, and were paid (1,000 Japanese yen) for their participation. All had normal vision and discrimination ability for the shapes and colors.

Materials, design, and procedure

Methodology was closely based on Experiment 1. The key difference for this experiment was that a "1144" reward pattern was used, with two target locations assigned a low (1-point) reward, and two assigned a high (4-point) reward (see Fig. 1). As with Experiment 1, the distribution of these rewards across the four target locations was randomly varied between trials. There were 288 trials, divided into four blocks of 72 trials.

Results and discussion

Recall accuracy is illustrated in Fig. 3. In this experiment, a feature-type factor (color or shape) significantly interacted with the reward factor $F(1, 19) = 5.03$, $MSE = .02$, $p = .037$, $\eta_p^2 = .20$, but this effect was not replicated in any other experiment (ps = .11, .97, and .39 in Experiments 1, 3, & 4, respectively). More importantly, there was not a significant three-way interaction (feature type, reward, and suffix). Thus, again, we collapsed these two feature types. A 2 × 2 ANOVA revealed a significant effect of reward, $F(1, 19) = 8.65$, $MSE = .04$, $p = .008$, $\eta_p^2 = .31$, with recall accuracy higher for Reward 4 ($M = .75$, $SE = .02$) than for Reward 1 ($M = .63$, $SE = .03$). There was also a significant effect of suffix, $F(1, 19) = 66.15$, $MSE = .01$, $p < .001$, $\eta_p^2 = .78$, with performance during no-suffix trials ($M = .73$, $SE = .03$) superior to suffix trials ($M = .65$, $SE = .03$). Finally, we observed a significant interaction between these factors, $F(1, 19) = 6.49$, $MSE = .01$, $p = .02$, $\eta_p^2 = .26$. Further comparisons (Bonferroni–Holm corrected, $p < .05$) revealed reward effects in both suffix conditions, but this advantage was larger on no-suffix trials (Cohen's $d = .80$) compared with suffix trials ($d = .48$). Similarly, the suffix effect was present in both reward conditions, but it was larger on Reward 4 trials ($d = 1.57$) than on Reward 1 trials ($d = .90$).

Experiment 2 therefore replicated the main effects of reward and suffix observed in the first experiment. Furthermore, when two items from within a display were assigned a high-reward value, the predicted interaction between reward and suffix was observed. This would fit with the view that participants in Experiment 1 were able to prioritize at least some of the low-reward items, thereby reducing the likelihood of us finding this Reward × Suffix interaction in that experiment. Increasing experimental control over which items are prioritized leads to observation of this predicted interaction. More generally, this experiment demonstrates that participants can prioritize more than one item from within a display; this results in increased accuracy for these items, but also in increased susceptibility to suffix interference.

Experiment 3

This experiment sought to further extend the outcomes observed so far, by exploring whether recall accuracy and vulnerability to interference are increased when three targets are highlighted for prioritization.

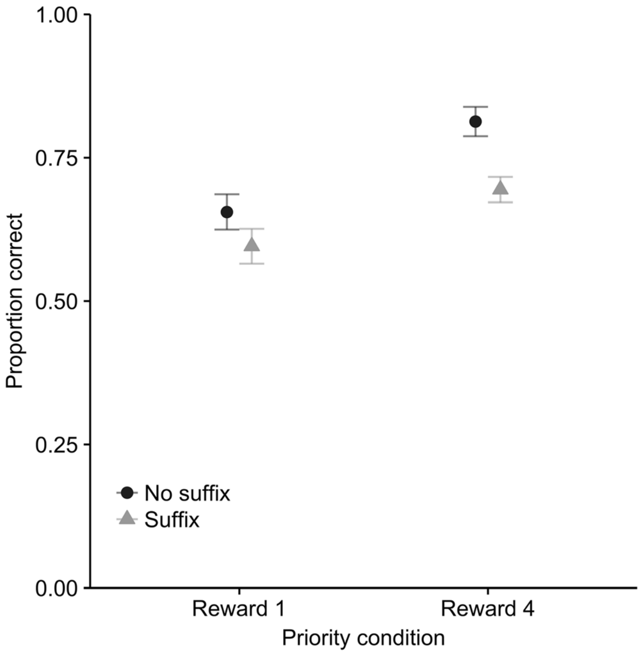

Fig. 3 Proportion correct (error bars show standard error) in Experiment 2

Method

Participants

Twenty undergraduate students (seven females, 13 males; $M_{age} = 19.05$, $SD = .22$) from Takachiho University, Japan, took part in the 45-minute experiment, and were paid (1,000 Japanese yen) or received an hour course credit for their

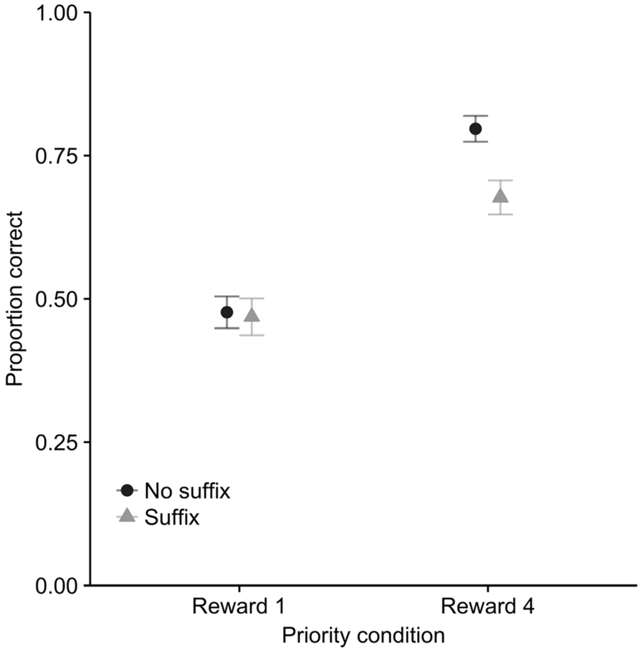

Fig. 4 Proportion correct (error bars show standard error) in Experiment 3

participation. All had normal vision and discrimination ability for the shapes and colors.

Materials, design, and procedure

Methodology was closely based on the previous experiments, with the exception that a "1444" reward pattern was implemented. Thus, one target location was assigned a low (1-point) reward, and three were assigned a high (4-point) reward (see Fig. 1). There were 256 trials, divided into four blocks of 64 trials.

Results and discussion

A 2 × 2 ANOVA revealed a significant effect of reward, $F(1, 19) = 39.32$, $MSE = .04$, $p < .001$, $\eta_p^2 = .67$, with recall accuracy higher for Reward 4 ($M = .74$, $SE = .03$) than for Reward 1 ($M = .47$, $SE = .03$). There was also a significant effect of suffix, $F(1, 19) = 17.20$, $MSE = .01$, $p < .001$, $\eta_p^2 = .48$, with performance during no-suffix trials ($M = .64$, $SE = .03$) superior to suffix trials ($M = .57$, $SE = .03$). Finally, we observed a significant interaction between these factors, $F(1, 19) = 13.51$, $MSE = .01$, $p = .002$, $\eta_p^2 = .42$. Further comparisons (Bonferroni–Holm corrected, $p < .05$) revealed reward effects in both suffix conditions, but this advantage was larger on no-suffix trials ($d = 1.65$) compared with suffix trials ($d = 1.01$). The suffix effect was present only on Reward 4 trials ($d = 1.70$), and not on Reward 1 trials ($d = .07$).

These findings therefore replicate and extend those observed in Experiment 2. Items assigned a higher reward value are recalled more accurately but are also more vulnerable to interference, relative to a low-reward item. This pattern emerges even when three items within an array are associated with a high reward, thus suggesting that participants can strategically prioritize multiple items in working memory.

Cross-experiment analysis of Experiments 1–3

Performance in the Reward 1 and Reward 4 conditions from across the three experiments so far ($N = 60$) were combined within a single 2 × 2 × 3 (Reward × Suffix × Experiment) mixed ANOVA. This was conducted to ascertain how the main effects and interactions might shift across experimental contexts in which the number of items to be prioritized changes (with Experiments 1–3 involving prioritization of one to three items respectively).

This analysis produced significant effects of reward, $F(1, 57) = 47.49$, $MSE = .03$, $p < .001$, $\eta_p^2 = .46$; suffix, $F(1, 57) = 96.02$, $MSE = .04$, $p < .001$, $\eta_p^2 = .63$; and experiment, $F(2, 57) = 5.08$, $MSE = .04$, $p = .009$, $\eta_p^2 = .15$.

Of greater interest are the pattern of interactions in this analysis. First, a Reward × Suffix interaction was observed, $F(1, 57) = 9.45$, $MSE = .01$, $p = .003$, $\eta_p^2 = .14$, in line with the interactive effects observed in Experiments 2 and 3.

The Reward × Experiment interaction was also significant, $F(2, 57) = 6.87$, $MSE = .01$, $p = .002$, $\eta_p^2 = .19$. Follow-up comparisons (Bonferroni–Holm corrected, $p < .05$) at Reward 1 indicated higher accuracy for Experiments 1 (.67) and 2 (.63), relative to Experiment 3 (.47). Thus, performance on the lowest value item declined when the number of high-value items increased from two to three. In contrast, there were no differences in Reward 4 accuracy between any of the experiments (Experiment 1 = .73; Experiment 2 = .75; Experiment 3 = .74), This indicates that the ability to prioritize any given item did not decline when the number of higher reward items was increased, and strongly supports the conclusion that it is possible to prioritize multiple items in a working-memory task.

The Suffix × Experiment interaction was not significant, $F(2, 57) = 1.50$, $MSE = .01$, $p = .23$, $\eta_p^2 = .05$. However, the three-way interaction between reward, suffix, and experiment was significant, $F(2, 57) = 5.97$, $MSE = .02$, $p = .004$, $\eta_p^2 = .17$. This was further explored by running separate 2 × 3 (Suffix × Experiment) mixed ANOVA on each of the Reward 1 and Reward 4 conditions. For Reward 1, a significant Suffix × Experiment interaction was observed, $F(1, 57) = 5.97$, $MSE = .01$, $p = .004$, $\eta_p^2 = .17$, while, for Reward 4, this interaction was not significant, $F(1, 57) = .87$, $MSE = .01$, $p = .424$, $\eta_p^2 = .03$. These outcomes confirm the patterns apparent across these experiments; the suffix effect on low-reward items reduces in size when the number of high-reward items is increased. These cross-experimental interactions also provide support for our explanation of the differing outcomes in Experiment 1, such that low-value items could also benefit from prioritization when there are fewer high-value items to prioritize. Nevertheless, it may be useful to further explore this pattern of differing effects in future studies.

Experiment 4

So far, we have observed that items within an array that are associated with a higher reward value (4 vs. 1 point) can be prioritized, with beneficial effects on recall accuracy but also concomitant increases in interference susceptibility. These results using simultaneously presented multi-item arrays are generally in line with those observed using serial presentation (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014). An interesting further question is whether differences in outcomes are observed when a graded distinction is made between different levels of reward. Can participants allocate varying degrees of attention to items associated with subtly different rewards, and does this also determine the magnitude of interference observed in each case? While Hu et al. (2014), Experiments 2 and 3 also implemented reward values ranging from one to four, this was confounded by serial position and was not fully orthogonally manipulated across the different positions in the sequence. The simultaneous presentation method used in the present study provides a more direct method of testing whether attention can be applied in a graded manner across targets.

Method

Participants

Twenty undergraduate students (16 females, four males; M_{age} = 20.75, *SD* = 2.90) from the University of York, UK, took part in the 45-minute experiment and were paid (4.00GBP) or received an hour course credit for their participation. All had normal vision and discrimination ability for the shapes and colors.

Materials, design, and procedure

In this final experiment, target locations were assigned either 1, 2, 3, or 4-point rewards (see Fig. 1). There were 288 trials, divided into four blocks of 72 trials. Randomly distributed across the experimental trials, each reward value was assessed 72 times (with 36 no-suffix trials and 36 suffix trials in each case).

Results and discussion

Recall accuracy is illustrated in Fig. 5. A 2 × 4 ANOVA revealed a significant effect of reward, $F(1, 19) = 31.44$, $MSE = .04$, $p < .001$, $\eta_p^2 = .62$. Follow-up analysis (Bonferroni–Holm corrected, $p < .05$) indicated significant differences between all reward levels (Reward 1 $M = .44$, $SE = .04$; Reward 2 $M = .49$, $SE = .03$; Reward 3 $M = .67$, $SE = .03$; Reward 4 $M = .73$, $SE = .03$). There was also a significant effect of suffix, $F(1, 19) = 32.95$, $MSE = .01$, $p < .001$, $\eta_p^2 = .63$, with performance during no-suffix trials ($M = .64$, $SE = .03$) superior to suffix trials ($M = .53$, $SE = .04$). Finally, we observed a significant interaction between these factors, $F(1, 19) = 3.41$, $MSE = .01$, $p = .023$, $\eta_p^2 = .15$. This interaction was further explored by examining the suffix effect at each reward value. This revealed significant suffix effects (Bonferroni–Holm corrected, $p < .05$) on Reward 2 ($d = .90$), Reward 3 ($d = .92$), and Reward 4 items ($d = 1.17$), but not on Reward 1 items ($d = .34$). Finally, a series of 2 × 2 ANOVAs comparing each reward value produced significant interactions (at $p < .05$) between reward and suffix when comparing Reward 1 with each of the other values, but not when comparing the other value conditions ($F < 1$, $p > .39$). Thus, the pattern of outcomes when comparing Reward 1 versus Reward 4 replicates findings from Experiments 2–3, and extends to comparisons of the lowest reward value with Rewards 2 and 3.

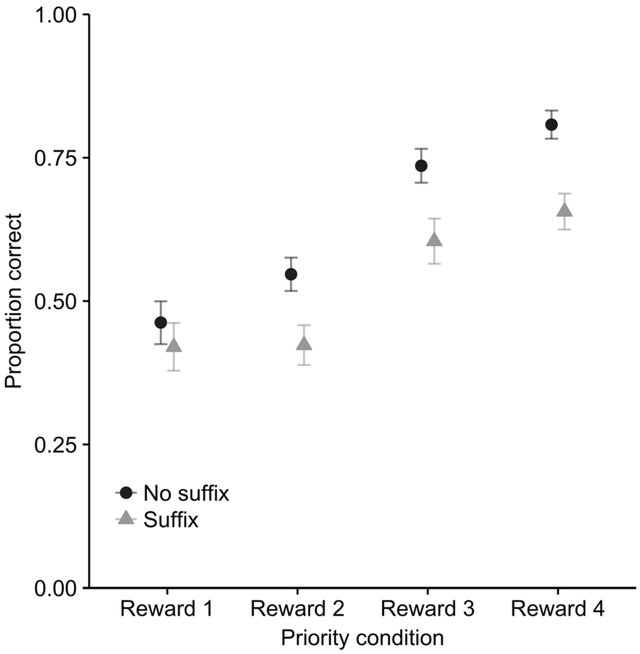

Fig. 5 Proportion correct (error bars show standard error) in Experiment 4

This experiment therefore indicates that items from within an array can be strategically prioritized in a graded manner according to associated reward. While accuracy levels on Reward 1 (.44) and 4 (.73) items were very similar to those observed in Experiment 3 (.47 and .74, respectively), performance on Reward 2 and Reward 3 items falls between these extremes. This suggests impressively flexible and subtle attentional control mechanisms that can be variably distributed across multi-item arrays and which help determine retrieval success. Suffix interference does not appear to be similarly graded (though numerically the suffix effects were ordered with reward value); any item that is associated with an increased reward becomes vulnerable to interference, to a broadly equivalent extent. As in Experiment 3 (which also implemented a three-item reward pattern), the item associated with the lowest reward value did not show any suffix interference.

General discussion

Across four experiments, we observed the ability to selectively prioritize items from within an array, based on their perceived reward values, thus extending recent outcomes from serial visual memory (Hu et al., 2016; Hu et al., 2014) to the processing of multi-item arrays. This is also in line with visual cueing effects applied during both encoding and maintenance of one-shot, multiple-item arrays (e.g., Griffin & Nobre, 2003; Schmidt et al., 2002), and with the ability to focus on targets and ignore simultaneously present distractions (e.g., Allen et al., 2017; Vogel, McCollough, & Machizawa, 2005a). This ability is not limited to a single item, as clear accuracy boosts were observed when participants were asked to prioritize multiple items (Experiments 2–4). This also extends work from serial visual memory (Hitch et al., 2018), and fits with the cueing literature demonstrating that multiple items can be selectively attended when cued during encoding (Makovski & Jiang, 2007; Schmidt et al., 2002) or maintenance (Awh & Pashler, 2000; Heuer & Schubö, 2016; Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura & Vecera, 2015). Experiment 4 takes these findings a step further and indicates not only that multiple targets can be prioritized, but that participants can vary the *degree* of prioritization in a relatively subtle manner. Finally, across the four experiments, we also consistently observed interference caused by presentation of a to-be-ignored suffix stimulus following target offset (Allen et al., 2015; Hu et al., 2016; Hu et al., 2014; Ueno, Allen, et al., 2011a; Ueno, Mate, et al., 2011b). These impacts of endogenous control and exogenous distraction were interactive (for Experiments 2–4), with larger and more consistent interference effects on higher reward items, compared with the item assigned the lowest points value.

What underlies the ability to prioritize as observed in this experimental series? When considering this question, it is important to note when reward values are allocated within the present paradigm. As this manipulation is applied prior to encoding, it is not possible to separate out mechanisms operating during encoding of the visual stimuli versus maintenance of resulting representations. Thus, it is likely that attention is directed toward higher reward items during the encoding phase, and that the extent to which each item is attended to can be controlled in a graded manner. Stimuli that are particularly attended to during encoding will then result in representations that may be more precise, robust, or accessible following target offset (Matsukura & Vecera, 2015). This may partly reflect spatially oriented selective attention mechanisms that are common to initial perception and subsequent retention (e.g., Awh & Jonides, 2001; Griffin & Nobre, 2003; Kuo, Rao, Lepsien, & Nobre, 2009), while processing within the oculomotor system may also be involved (Theeuwes, Belopolsky, & Olivers, 2009). Examination of fixation patterns during encoding and retention would be informative in this regard. In addition, given the relatively extended presentation duration (2 s) used in the present series, it may be instructive for future work to examine whether outcomes shift when using considerably reduced exposures, and specifically whether participants become less able to prioritize multiple items, or apply graded prioritization as seen in Experiment 4. Following target offset, processes underlying prioritization are likely to then continue into maintenance, with more resources allocated to consolidation and/or attentional refreshing (Chun & Johnson, 2011; Rerko & Oberauer, 2013; Rerko et al., 2014; Souza, Rerko, Lin, & Oberauer, 2014a; Souza, Rerko, & Oberauer, 2014b) of high-reward items. In the latter case, this would require that refreshing is selectively applied to certain items rather than involving a rigid cycling of all targets in the array.

An assumption of our work to date concerning reward-based prioritization has been that prioritized items are held in a relatively accessible or privileged state (Hu et al., 2016; Hu et al., 2014). We equated this state with a focus of attention (Cowan, 1995, 2005; Oberauer & Hein, 2012), and suggested that this may represent the contents of the episodic buffer, within a multiple component view of working memory (Baddeley, 2012). Estimates of the number of items that can be held concurrently within the focus of attention vary between approaches, with Cowan (2001) suggesting three to four items, while Oberauer (e.g., Oberauer & Hein, 2012; Souza, Rerko, & Oberauer, 2014a) has argued for a one-item focus unless items are so dissimilar as to avoid mutual interference. The present results would suggest that up to three targets can be held together within the focus of attention, with little to no cost between these items. An alternative explanation may be that only one item is held within the focus of attention at any time, but that multiple items can be prioritized through the selective direction of attentional selection during encoding and consolidation, and the attentional refreshing of these items whereby they are rapidly cycled through the focus of attention during maintenance. However, this latter account might predict that increasing the number of high-reward items would reduce their recall accuracy. In fact, performance on high-reward items was strikingly consistent across the four experiments (.73–.75 in each case), indicating that participants could prioritize three targets as successfully as a single target, although this came with increasing costs to low-reward items. We would, of course, anticipate that continuing to increase the number of high-reward items would eventually lead to declines in performance as capacity or resource limitations are reached; indeed, it would be interesting for future work to examine the point at which this starts to occur, whether there are reliable differences between individuals, and the extent to which noncategorical (i.e., precision-based) measures (e.g., Bays & Husein, 2008) detect similar changes in performance. We would also expect that the number of targets that can be prioritized will vary across different materials and task contexts.

Based on the consistent observation from serial visual memory that a to-be-ignored suffix item particularly disrupts both the prioritized item and the most recently encountered item in the sequence (Hu et al., 2016; Hu et al., 2014), the benefits of accessible storage within the focus of attention also comes with heightened vulnerability to interference. This conclusion was extended in the present experimental series to memory for simultaneously encountered multi-item arrays, though only when the number of high-reward items was sufficient to reduce participants' ability to also prioritize low-reward items (i.e., Experiments 2–4). These findings are convergent with a view of the focus of attention within working memory as temporarily retaining a limited amount of accessible information that is in constant flux, due to the push and pull of internal control and external input. Thus, goal-relevant information can be prioritized and held in an accessible state, but this can also be disrupted by the sudden onset of newly encountered information, in line with a view of the focus of attention as an active state that closely interacts with sensory processing (Hollingworth & Hwang, 2013; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Ueno & Saito, 2013). In contrast, items that are not held in the focus of attention (i.e., low-reward targets) show minimal suffix interference (Experiments 3 and 4). This is consistent with evidence of a separate neural basis for temporary storage that is outside the focus of attention (Lewis-Peacock et al., 2012). This form of storage appears to be less readily accessible but also less responsive and sensitive to changes in the environment.

The final experiment also demonstrated that any item that is being prioritized becomes more vulnerable to subsequent interference, regardless of associated value. Increasing reward values from two to four resulted in accompanying accuracy improvements, but suffix interference effects did not scale with this; each of these items showed statistically equivalent interference effects. Speculatively, this might imply that the graded prioritization effects observed in Experiment 4 do not reflect the varying probability of an item being held in the focus of attention. Instead, all to-be-prioritized items (up to a capacity limit) may be equally likely to be held in the focus of attention, but the precise value of an item may influence how it is attended during encoding, determining factors such as memory strength or resolution. However, a statistically non-significant Suffix × Reward interaction between values two through four does not necessarily imply equivalence, particularly given the relatively small number of participants and few trials per condition. We would note that sample size calculations were based on a comparison of highest versus lowest reward values, rather than more fine-grained comparisons. Furthermore, suffix interference effect size was slightly larger for the highest reward item, relative to Rewards 2 and 3. Further work is undoubtedly required to understand how graded reward values are translated into attentional processing and working-memory functioning.

The observation that prioritized high-reward items are more accurately recalled but also more susceptible to interference therefore appears to be consistent, emerging across presentation formats (serial and simultaneous) and methods of reward allocation (based on either temporal or spatial position). Why are contrasting outcomes apparent in visual cueing studies, instead showing that cueing attention toward an item (e.g., via a cue during maintenance) is unaffected by, or even increases protection from, subsequent visuospatial interference (e.g., Hollingworth & Maxcey-Richard, 2013; Makovski & Jiang, 2007; Makovski et al., 2008; Souza & Oberauer, 2016)? One possibility is that this reflects differences in how prioritization and cueing manipulations are implemented, and the impacts these have on the drivers of attentional selection. Our explorations of reward-based prioritization to date (the present study; Hitch et al., 2018; Hu et al., 2016, Hu et al., 2014) have used nonpredictive reward schemes, with high-reward and low-reward items being equally likely to be tested. In these circumstances, participants are encouraged to prioritize one or more target items while also attempting to process additional items of lower value. In contrast, cueing studies (e.g., Makovski et al., 2008), particularly those exploring interference effects, typically use highly predictive cues (often at 100% validity with the test item). While both forms of attentional direction result in improved memory for targeted items, they cannot be assumed to operate in the same way (Atkinson et al., 2018). For example, contrasting outcomes may reflect differences between modes of attention in visual working memory. Specifically, Makovski and Jiang (2007) showed that when to-be-tested items are precued before the target array, then multiple items can be enhanced (i.e., in a distributed mode of attention), but only one item can be enhanced (i.e., a focused attentional mode) when to-be-tested items are retro cued after the target offset. Our reward manipulation is closer to the precue methodology as the reward values were presented before the target array, and multiple high-reward items featured in Experiments 2–4. Furthermore, the nonpredictive nature of these rewards means that participants must attempt to encode the entire array even while focusing on a subset of items. In this context, we might speculate that a distributed mode of attention is engaged, in which high-reward items are prioritized but left vulnerable to interference. In contrast, contexts that promote focused attention (e.g., when a single item is cued with 100% validity) may allow for the protection of the cued item from interference.

The present results are part of an emerging picture indicating that the direction of attention can influence visual memory, and that this can be achieved via different manipulations (e.g., Atkinson et al., 2018; Griffin & Nobre, 2003; Hu et al., 2014; Makovski & Jiang, 2007; Schmidt et al., 2002; Siegel & Castel, 2018; Thomas et al., 2016). While these findings generally indicate improved recall or recognition for the selected targets, differences are apparent in how such beneficial effects interact with features of the broader task context. Further work will be needed to systematically map out the mechanisms underlying the effects of attentional selection and interference across different conditions. Deriving a plausible model with explanatory power that extends across task contexts would be of considerable benefit both in understanding memory and attention at a theoretical level, and in helping identify the conditions under which memory and attention might be optimized in a practical sense.

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Appendix

Table 1 Mean recall accuracy (and standard errors in parenthesis) in color and shape trials, respectively

	Color		Shape	
	No suffix	Suffix	No suffix	Suffix
Experiment 1				
Reward 1	.74 (.04)	.63 (.04)	.71 (.04)	.59 (.04)
Reward 4	.78 (.04)	.68 (.05)	.78 (.05)	.70 (.04)
Experiment 2				
Reward 1	.65 (.03)	.59 (.03)	.66 (.04)	.60 (.03)
Reward 4	.83 (.02)	.73 (.03)	.80 (.03)	.66 (.02)
Experiment 3				
Reward 1	.48 (.04)	.47 (.03)	.47 (.03)	.47 (.04)
Reward 4	.79 (.02)	.69 (.03)	.81 (.02)	.66 (.03)
Experiment 3				
Reward 1	.51 (.05)	.41 (.05)	.42 (.04)	.43 (.05)
Reward 2	.59 (.03)	.47 (.05)	.50 (.04)	.38 (.03)
Reward 3	.74 (.04)	.63 (.04)	.73 (.03)	.58 (.04)
Reward 4	.82 (.03)	.68 (.04)	.80 (.03)	.63 (.03)

Table 2 Mean proportion of each error types (and standard errors in parenthesis)

	Within-list confusion		Outside-list intrusion		Suffix intrusion
	No suffix	Suffix	No suffix	Suffix	
Experiment 1					
Reward 1	.17 (.02)	.23 (.03)	.11 (.02)	.05 (.01)	.04 (.01)
Reward 4	.17 (.03)	.20 (.03)	.15 (.01)	.11 (.02)	.06 (.01)
Experiment 2					
Reward 1	.20 (.03)	.18 (.03)	.15 (.01)	.23 (.01)	.07 (.01)
Reward 4	14 (.02)	.19 (.03)	.05 (.01)	.11 (.01)	.04 (.01)
Experiment 3					
Reward 1	.31 (.03)	.32 (.03)	.21 (.02)	.20 (.02)	.08 (.01)
Reward 4	.14 (.02)	.27 (.03)	.06 (.01)	.05 (.01)	.01 (.01)
Experiment 3					
Reward 1	.31 (.03)	.32 (.03)	.23 (.02)	.26 (.03)	.08 (.01)
Reward 2	.28 (.02)	.31 (.02)	.18 (.02)	.27 (.02)	.08 (.01)
Reward 3	.16 (.02)	.24 (.03)	.10 (.02)	.16 (.02)	.05 (.01)
Reward 4	.13 (.02)	.20 (.02)	.06 (.01)	.14 (.02)	.04 (.01)

Note. Within-list confusions consist of recall of a feature from another presented item than the one probed. Outside-list intrusions consist of recall of a feature that was not included among the memory items. Suffix intrusion refers to recall of a feature from the suffix presented in that trial. Note that outside-list intrusion includes the suffix intrusion (i.e., rates of correct recall, within-list intrusion, and outside-list intrusion sum up to 1)

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