Prioritization within visual working memory reflects a flexible focus of attention

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Abstract

When motivated, people can keep nonrecent items in a list active during the presentation of new items, facilitating fast and accurate recall of the earlier items. It has been proposed that this occurs by flexibly orienting attention to a single prioritized list item, thus increasing the amount of attention-based maintenance directed toward this item at the expense of other items. This is manipulated experimentally by associating a single distinct feature with a higher reward value, such as a single red item in a list of black items. These findings may be more parsimoniously explained under a distinctiveness of encoding framework rather than a flexible attention allocation framework. The retrieval advantage for the prioritized list position may be because the incongruent feature stands out in the list perceptually and causes it to become better encoded. Across three visual working memory experiments, we contrast a flexible attention theory against a distinctiveness of encoding theory by manipulating the reward value associated with the incongruent feature. Findings from all three experiments show strong support in favor of the flexible attention theory and no support for the distinctiveness of encoding theory. We also evaluate and find no evidence that strategy use, motivation, or tiredness/fatigue associated with reward value can adequately explain flexible prioritization of attention. Flexible attentional prioritization effects may be best understood under the context of an online attentional refreshing mechanism.

Keywords Visual working memory · Attention · Flexibility · Cognitive control · Distinctiveness · Prioritization · Motivation · Strategy · Reward

Our ability to orient or direct our attention to internal memory representations is a fundamental cognitive ability (Posner, 1980). Whether or not we can flexibly adjust the contents of our focus of attention, the capacity-limited region within working memory (Cowan, 1988, 2001, 2005; Oberauer, 2002), is less well established. Some interpret faster responses to only the most recent item in a sequentially presented list, the recency item, as evidence that the capacity of the focus of attention is restricted to a single item (McElree, 1998, 2006; McElree & Doshier, 1989; Nee & Jonides, 2008, 2011; Oberauer, 2002; Oberauer & Bialkova, 2009; Öztekin, Davachi, & McElree, 2010). Contrary evidence suggests that

the focus of attention can accommodate about three to five items (Cowan, 2010; Gilchrist & Cowan, 2011). It is possible that both views are correct. The focus of attention may operate as a flexible resource that can be adjusted to maintain nonrecent information (Allen & Ueno, 2018; A. L. Atkinson et al., 2018; A. L. Atkinson, Waterman, & Allen, 2019; Hitch, Hu, Allen, & Baddeley, 2018; Hu, Allen, Baddeley, & Hitch, 2016; Hu, Hitch, Baddeley, Zhang, & Allen, 2014; Morrison, Conway, & Chein, 2014; Sandry, Schwark, & MacDonald, 2014) or an adjustable resource that can zoom in or zoom out to maintain variable amounts of information (Cowan et al., 2005; Eriksen & St James, 1986; Oberauer & Hein, 2012).

In past research, the only situations where the last-item advantage could be overcome, and nonterminal sequentially presented information could be maintained in a more accessible state than the final list item, was when there was additional time available to process or rehearse the information (McElree, 2001, 2006). Contrary to these findings, Sandry et al. (2014) showed support for a flexible focus of attention for sequentially presented information. Participants completed a sequentially presented verbal probe-recognition task coupled with a reward manipulation. On some trials, attention

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was directed toward a single list item by presenting it in red font and assigning it a higher reward point value for correct recognition (and equivalent loss of points for incorrect recognition). High and low point list positions were equally likely to be probed. Participants were able to maintain the older non-terminal prioritized items in a more accessible state, as evidenced by shorter response times (RTs) for prioritized items compared with the control condition and compared with the final item in the list (recency). Flexibility came at the expense of other list positions in the form of a resource trade-off, whereby the RTs for nonprioritized list positions were longer than in a control condition. The effect was robust under articulatory suppression, ruling out rehearsal as an explanation for flexibility. The privileged status for the prioritized item provides unique evidence that the focus of attention is a flexible resource, even for sequentially presented information. One alternative explanation that we evaluate in the current study is whether these earlier findings are due to distinctiveness of encoding and not to the flexibility of attention. The flexible-attention theory argues that the prioritized list item benefits from the flexible continued allocation of attention toward its internal representation, whereas the distinctiveness of encoding account argues that visual features of the prioritization cue itself lead to improved encoding of the item and improved memory performance.

It is possible that changing a single feature (color) of one list item resulted in better memory performance because this item was more distinct at encoding. This effect, the von Restorff isolation effect, is well documented in some contexts (Hunt, 1995; Schmidt, 1991; von Restorff, 1933; Wallace, 1965) and suggests that in groups of items, those items with distinct features are better remembered than items that all share a common feature. Simply put, participants in the Sandry et al. (2014) investigation may have been able to remember high-point list positions because the red items stood out and not because participants were able to flexibly allocate their attention to those items. The conclusions of the Sandry et al. investigation are also limited to verbal memory items. It remains unclear whether or not the prioritization effect in the present paradigm extends to nonverbal information in working memory.

Reward and cognition

An additional question raised by these findings is, What underlying cognitive mechanism is responsible for reward-related prioritization effects? The reward manipulation may cause participants to adopt and employ different working memory strategies to effectively maintain the prioritized item. This would imply that attention is not flexibly allocated, but instead a fundamentally different cognitive process is used to maintain prioritized information. The reward manipulation

may also alter participants' level of motivation or their degree of engagement and effort devoted to the task, resulting in the prioritization benefits observed by Sandry et al. (2014).

There is a robust literature dedicated to understanding how rewards and incentives affect cognitive control mechanisms. Pertinent to the current research, reward directly affects selective attention performance (Anderson, 2013, 2016; Engelmann, Damaraju, Padmala, & Pessoa, 2009; Engelmann & Pessoa, 2014; Krebs, Boehler, Roberts, Song, & Woldorff, 2011; Small et al., 2005), and reward and attention are difficult concepts to disentangle (Maunsell, 2004). Learning and memory ability (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Dickerson & Adcock, 2018; Wittmann et al., 2005), as well as working memory performance (Gilbert & Fiez, 2004; Jimura, Locke, & Braver, 2010; Krawczyk, Gazzaley, & D'Esposito, 2007; C. C. Morey, Cowan, Morey, & Rouder, 2011; Taylor et al., 2004), are also cognitive processes that are directly affected by reward. One main finding across these related lines of research is that the modulation of cognitive control and related improvement in task performance as a result of increased reward is partially a result of increased motivation (Botvinick & Braver, 2015). High motivation, for example, improves memory performance (Harley, 1965; Weiner, 1966; Weiner & Walker, 1966), and in some instances this is because participants implement a rehearsal strategy to help them better maintain to-be-remembered information (R. C. Atkinson & Wickens, 1971; Eysenck & Eysenck, 1980, 1982).

High reward also affects performance by causing participants to become less susceptible to tiredness and fatigue, allowing them to exert more effort and remain engaged on the task for longer periods of time (Boksem & Tops, 2008; Dobryakova, DeLuca, Genova, & Wylie, 2013). On the other hand, low reward is related to increased feelings of tiredness and fatigue that can ultimately lead to decrements in task performance (Boksem & Tops, 2008). Changes in motivation and tiredness/fatigue or adjustments in working memory strategy use as a function of a reward manipulation may be partially responsible and help explain past behavioral findings demonstrating support for a flexible focus of attention. Thus, we also evaluate how reward indirectly affects motivation, fatigue, and working memory strategy use, thereby contributing to our ability to flexibly adjust focus of attention resources within working memory.

Present experiments

Across three visual working memory experiments, using simple shapes (Experiment 1), spatial directions (Experiments 2), and unfamiliar characters (Experiment 3), we present a list of three memory items, one of which is presented in red and the other two items which are presented in black. Critically, we

manipulate the point structure across conditions. In the high-reward condition, correct responses to the red items are worth more points than are correct responses to the black items. In the equal-reward condition, responses to both the red and black items are worth the same number of points. In a control condition, all items are presented in black.

This experimental approach allows us to answer four important questions. First, by manipulating the point structure of the experiment between participants, we can directly evaluate whether distinctiveness of encoding can explain the shorter RTs observed for the prioritized red item compared with black control items in previous research. Flexible attention and distinctiveness of encoding theories make different predictions about the pattern of results expected in response to our manipulation of the reward conditions. The flexible-attention theory predicts that in the equal-reward condition, when participants are not motivated to preferentially direct attention to the red items, their RTs to red memory-item probes will not differ from black memory items in the same serial positions of the control condition. The distinctiveness of encoding theory predicts that in the equal-reward condition, when participants are not motivated to preferentially direct attention to the red items, their RTs to red memory-item probes will be considerably faster than responses to black memory items in the same serial positions.

Second, we measure self-reported strategy use to determine whether the reward manipulation used in the current paradigm causes participants to adopt different maintenance approaches. Third, given strong links between reward, motivation, and cognitive performance (Botvinick & Braver, 2015), we test how motivation and tiredness/fatigue may change as a function of the reward manipulation. Fourth, we test whether the pattern of resource trade-offs that allows improved performance for high-reward memory items at the expense of low-reward memory items using verbal memoranda replicates when the memory items are visual in nature. These aims provide insight into the underlying cognitive mechanisms resulting in the prioritization benefit in working memory.

Method

We present three experiments investigating whether the resource trade-off between prioritized and nonprioritized memory items is due to flexible attention or distinctiveness of encoding, while simultaneously evaluating possible reward-related mediators of prioritization. All stimuli are visual in nature, but differ in their exact properties across experiments. Point structure is manipulated between participants. There is no articulatory suppression. All design and procedural aspects remain identical across experiments except for the memory stimulus materials. This difference across experiments allows us to examine further whether the pattern of results follows

from the nature of the presented stimulus and the cognitive processing that they afford.

Participants

Students from Montclair State University participated for partial course credit, and $N = 69$ were included in Experiment 1, $N = 69$ in Experiment 2, and $N = 72$ in Experiment 3. We demonstrated reliable within subject effects with sample sizes of $N = 24$ participants in previous research. We estimated needing slightly more participants per group ($\sim N = 30$) given between-participant variability associated with the point-value manipulation. We advertised time slots at the start of each week and concluded posting advertisements after meeting our minimum recruitment goal.

Materials and design

Visual stimuli were 12 simple shapes in Experiment 1 (see Fig. 1), eight arrows, each pointing in one of the following directions, 0° , 45° , 90° , 135° , 180° , 225° , 270° , or 315° in Experiment 2, and 204 unfamiliar characters taken from Ricker and Cowan (2014) in Experiment 3. Visual stimuli were presented in either red or black font on a gray background. No stimuli were duplicated within any individual trial. The design was a 2 (point value: high reward, equal reward) $\times$ 4 (prioritization position¹: red stimulus in the first, middle, or last list position, or no red stimulus in the list [control]) $\times$ 3 (probe position: first, middle, or last) mixed-participant design, with point value manipulated between participants, and prioritization position and probe position manipulated within participants.

Procedure

The task took the form of a memory game. Three visual stimuli were presented sequentially, followed by a two-alternative forced-choice (2AFC) recognition test (see Fig. 1). The probe-recognition task was combined with a value manipulation. Participants could lose or gain points for incorrect or correct responses. Participants were instructed to try and earn as many points as possible. In the high-reward condition, black stimuli were worth 3 points, and on 75% of trials, one list item was presented in red font and worth 25 points. In the equal-reward condition, both black and red colored stimuli were worth an equivalent 3 points each. Trials started with a blank intertrial interval (.25 s) followed by a fixation asterisks (.5 s), and then three to-be-remembered stimuli were sequentially presented (.5 s each) followed by a mask (.5 s). Finally, one list stimulus

¹ We previously referred to this factor as “orientation position” (Sandry et al., 2014), but use “prioritization position” henceforth to remain congruent with the working memory prioritization literature.

Fig. 1 Procedure used in all experiments, illustrated with simple shape stimuli from Experiment 1. See main text for timings. SP = serial position

and one novel stimulus were presented side by side on the 2AFC choice screen (2.5 s). There was an equal probability of the list stimulus appearing on the left or right. Participants indicated the stimulus that was from the list using a key press. The list stimulus presented at test had an equal probability of being selected from each list position. All trials were followed by feedback informing participants of how many points they earned or lost on that trial, along with their total accumulated points (1.5 s). All stimuli were randomly drawn without replacement from the larger stimulus set.

Participants completed 300 experimental trials with 30-second breaks occurring every 50 trials. The break screen included a report of overall accuracy and point total along with accuracy and point total for each individual block completed. Twenty-five trials on average were presented for each cell of the design. Participants completed 10 practice trials with an optional repetition before moving on to experimental trials. Participants were tested in a small room with up to four people seated at individual cubicles.

Posttask questionnaire After completing the experiment, participants completed a posttask questionnaire to evaluate working memory strategy use along with levels of motivation and tiredness/fatigue. To evaluate strategy use, participants were presented with a list of 10 alternative working memory strategies (adapted from Morrison, Rosenbaum, Fair, & Chein, 2016; see Table 1) and asked to select the strategy that best described how they remembered the stimuli (shapes, arrows,

or characters, Experiments 1, 2, and 3, respectively). The 10 strategy choices were presented in randomized order for each participant. Attentional allocation priorities can themselves be viewed as a type strategy. The questionnaire was intended to address other uses of strategy during task performance. After answering the strategy-use question, participants proceeded to answer three self-report questions about their overall level of motivation and tiredness/fatigue. The motivation questions asked participants “How motivated were you to score a high number of points?” and “Overall, how motivated were you throughout the experiment?” The tiredness/fatigue question asked participants “How tired were you while performing the experiment?” Participants made their responses using a continuous sliding scale from 0 (*not at all*) to 100 (*extremely*).

Results and discussion

We are primarily interested in how attentional allocation changes as a function of the points manipulation. Participants were excluded from all analyses for performing at or below chance levels of performance ($N = 1$ Experiment 1; $N = 6$ Experiment 2). Additionally, to avoid contamination from low-performing participants, whose effort and attention to the task could not be verified, we excluded participants who performed ≤ 2 standard deviations below group-level accuracy along with participants with abnormally short RTs, ≤ 2 standard deviations shorter than the group-level mean ($N = 6$

Table 1 Strategy-use questionnaire adapted from Morrison, Rosenbaum, Fair, and Chein (2016)

Strategy	Description of strategy used on questionnaire
Rehearsal	I silently repeated the shapes/arrows/characters
Grouping	I remembered the shapes/arrows/characters in groups (e.g., 2 or more shapes/arrows/characters together)
Association	I thought about other things that could relate to the shapes/arrows/characters
Look	I pictured the way the shapes/arrows/characters looked on the screen
Sound	I thought about the way the shapes/arrows/characters sounded
Concentrate	I simply concentrated on the shapes/arrows/characters
Familiarity	I answered based on what shapes/arrows/characters seemed recent or familiar
Checklist	I expected certain shapes/arrows/characters to appear and mentally checked them off as they arrived
None	None, I used no particular strategy
Other	Other (I used a different strategy that is not listed here)

Note. Participants were asked to “Please select the strategy below that best describes how you remembered the shapes/arrows/characters.” Order of response options were randomized across participants. No participants endorsed not using a strategy (None). Morrison et al. also included options for “Semantic” and “Imagery” strategies that we did not include, given the nature of the stimuli in the present experiments were intentionally nonverbal (visual) stimuli

Experiment 1; $N = 4$ Experiment 2; $N = 6$ Experiment 3). Response time for accurate trials served as the main dependent measure and an index of speed of retrieval from the focus of attention (McElree, 2006; Morrison et al., 2014; Oberauer, 2002; Sandry et al., 2014; Vergauwe et al., 2016). Individual trials were removed if the trial RT was an outlier. Response-time outliers were operationalized as RTs shorter than 300 ms or longer than 3 standard deviations above the participant’s mean in each experimental condition (Oberauer, 2002; Sandry et al., 2014). This procedure resulted in removal of 2.06% (Experiment 1), 1.14% (Experiment 2), and 1.81% (Experiment 3) of trials. We also present an analysis of task accuracy, for completeness, and 2 (point value) $\times$ 4 (prioritization position) $\times$ 3 (probed position) mixed-measures Bayesian analyses of variance (ANOVAs) were computed along with simple comparisons to investigate the nuances of the data pattern.

Data analysis

We use Bayes factors for t tests (Rouder, Speckman, Sun, Morey, & Iverson, 2009) and ANOVAs (Rouder, Morey, Speckman, & Province, 2012) as our main measures of statistical inference. In this context, we present Bayes factors as the ratio between the probability of the data given that an effect is present (the alternative hypothesis) to the probability of the data given that an effect is not present (the null hypothesis). A Bayes factor value of 8 in support of an effect should be interpreted as the alternative hypothesis being 8 times more likely than the null hypothesis, given the data. All analyses were computed using the default settings of the BayesFactor package (R. D. Morey & Rouder, 2015) in R (Version 3.3.2; R Core Team, 2016).

Experiment 1: Simple shapes

Response time Mean RTs for each prioritization position and serial position as a function of point value are presented in Fig. 2a. The main question of interest is whether there is a difference in performance for the red items between the high-reward and equal-reward conditions. It is clear in the figure that red list positions in the high-reward condition were responded to more quickly than control probes. This pattern is not evident for red list positions in the equal-reward condition when compared with control probes. This pattern was statistically supported by a three-way interaction, $F(6, 360) = 7.76$, $\eta_p^2 = .11$, $BF = 9.11 \times 10^3$, in favor of an effect. Bayesian repeated-measures t test comparisons between red prioritized positions and black control positions in the same serial position for each of the three probe positions were further investigated to fully understand differences in performance patterns (e.g., Serial Position 1 when it was red compared with Serial Position 1 when there were no red items). Bayes factor t tests favored an effect of shorter RTs for prioritized positions (red items) compared with control items in the same probe position for the high-reward condition for Probe Position 1, $t(28) = 3.25$, $BF = 13$; Probe Position 2, $t(28) = 2.84$, $BF = 5$; and Probe Position 3, $t(28) = 3.63$, $BF = 31$. This pattern was not observed in the equal-reward condition, where there was no evidence that red positions differed from control positions (all $BFs < 1$).

Accuracy There was evidence for the presence of a three-way interaction between all three manipulations in accuracy, $F(6, 360) = 5.33$, $\eta_p^2 = .08$, $BF = 818$ (see Fig. 3a). Analysis of the individual comparisons revealed weak evidence in the direction of higher accuracy for prioritized positions compared with control positions in the high-reward condition, for

◀ **Fig. 2** Mean RT for probe position and prioritization as a function of between participants point value condition for Experiments 1, 2, and 3, Panels **a**, **b**, and **c**, respectively. The red colored bars represent the list positions prioritized to in red, and the black colored bars represent the list control positions. Labels on the x-axis (SP 1 Red, etc.) correspond to trials with the matching label in Fig. 1. Numerical values (1, 2, 3) above the x-axis labels indicate probed serial position. Error bars represent 1 standard error. SP = serial position. *Note.* Range is maintained; however, min and max values of ordinate axis in Panel **b** differs from Panels **a** and **c**

Probe Position 1, $t(28) = 2.44$, $BF = 2$; Probe Position 2, $t(28) = 2.55$, $BF = 3$; and some evidence against a difference for Probe Position 3, $t(28) = .72$, $BF = .25$. There was no evidence that accuracy for prioritized positions differed from the control positions in the same serial position under the equal-reward condition (all $BFs \leq 1$). While the evidence for the individual comparisons in accuracy are weak, the pattern of accuracy findings in Fig. 3a is consistent with the RT data in all conditions, with no evidence for a trade-off between accuracy and RT.

Posttask questionnaire Forty-eight percent (high-reward $N = 16$; equal-reward $N = 14$) of participants reported using a rehearsal strategy on the posttask questionnaire (see Fig. 4).² Motivation to score points, level of tiredness, and overall motivation produced no evidence of a difference as a function of the point-value manipulation (all $BFs < 1$; see Table 2).

Discussion In Experiment 1, RTs for red list positions in the high-reward condition were responded to more quickly than in the equal-reward condition, in support of a flexible focus of attention. A similar pattern but less pronounced effect is evident for accuracy. These data suggest that the points associated with the red list position drove the effect and not the color alone, in opposition to a distinctiveness of encoding theory. While the stimuli were visual in nature, the responses to the posttask questionnaire suggest, somewhat unexpectedly, that nearly half of the participants reported using a rehearsal strategy. Participants may have assigned a verbal label to the stimuli—for example, “square,” “circle,” “triangle”—and repeated the verbal label over the short presentation interval. The additional motivation and tiredness/fatigue questions on the posttask questionnaire suggest that there were no differences in level of motivation to score points, level of tiredness or overall motivation devoted to the task as a function of between participant conditions, making it unlikely that these factors can account for the behavioral findings.

While Experiment 1 begins to rule out distinctiveness of encoding, it is possible that rehearsal interacts with the reward manipulation for visual information, and this contributed to faster access to the content of the focus of attention. In

Experiment 2, we address this concern and reevaluate the same predictions by replicating all aspects of Experiment 1, but change the memory stimuli from shapes to arrows pointing in one of eight different directions. Our rationale is that participants may be less likely to verbally recode the directional arrows compared with the easily named shapes.

Experiment 2: Spatial directions

Response time The prioritized red list positions in the high-reward condition were responded to more quickly than control probes. This pattern is not evident for prioritized red list positions in the equal-reward condition (see Fig. 2b). This pattern was statistically supported by a three-way interaction, $F(6, 342) = 11.32$, $\eta_p^2 = .17$, $BF = 1.79 \times 10^7$, in favor of an effect. Bayes factor t tests comparisons favored an effect of shorter RTs for prioritized positions (red items) compared with control items in the same probe position for the high-reward condition for Probe Position 1, $t(29) = 2.94$, $BF = 7$; Probe Position 2, $t(29) = 4.58$, $BF = 312$; and Probe Position 3, $t(29) = 5.46$, $BF = 2937$. This pattern was not observed in the equal-reward condition, where prioritized red positions showed no evidence of differing from control positions (all $BFs \leq 1$).

Accuracy There was evidence for a three-way interaction between all three manipulations, $F(6, 342) = 3.30$, $\eta_p^2 = .05$, $BF = 7.08$ (see Fig. 3b). Analysis of the individual comparisons rendered similar patterns to the previous experiment, with weak evidence for higher accuracy for responses for prioritized positions compared with control positions in the high-reward condition for Probe Position 1, $t(30) = 2.27$, $BF = 2$, and weak evidence against a difference in accuracy for Probe Position 2, $t(30) = 1.53$, $BF = .60$, and Probe Position 3, $t(30) = .79$, $BF = .26$. Accuracy for prioritized positions showed no evidence of differing from the control positions in the same serial position under the equal-reward condition (all $BFs \leq 1$).

Posttask questionnaire Thirty-nine percent of participants (high-reward $N = 10$; equal-reward $N = 13$) endorsed the use of a rehearsal strategy (see Fig. 4). Motivation to score points, level of tiredness, and overall motivation produced no evidence of a difference as a function of the point-value manipulation (all $BFs < 1$; see Table 2).

Discussion Response-time analyses in Experiment 2 provides converging support for the flexible-attention theory proposing that the focus of attention can orient to and maintain nonrecent visuospatial information while simultaneously ruling out the distinctiveness of encoding theory. As with Experiment 2, the pattern for accuracy matched RT, but with weak statistical support for the simple comparisons. The posttask questionnaire findings again suggest that some participants used a

² Formal statistical analysis of the role of rehearsal in prioritization effects are reported in the Combined Analysis Across Experiments section of the results.

Fig. 3 Mean accuracy for probe position and prioritization as a function of between participants point value condition for Experiments 1, 2, and 3, panels **a**, **b**, and **c**, respectively. The red colored bars represent the list positions prioritized to in red, and the black colored bars represent the control list positions. Labels on the *x*-axis (SP 1 Red, etc.) correspond to trials with the matching label in Fig. 1. Numerical values (1, 2, 3) above the *x*-axis labels indicate probed serial position. Error bars represent 1 standard error. SP = serial position. *Note.* Range is maintained; however, min and max values of ordinate axis in Panel **b** differs from Panels **a** and **c**

rehearsal strategy. These participants may have assigned labels to the visuospatial stimuli and rehearsed those labels over the short presentation interval. Therefore, we designed Experiment 3 to further rule out rehearsal as a plausible alternative to attentional focusing and changed the stimuli to unfamiliar characters that are difficult to verbally relabel in a useful manner (Ricker, Cowan, & Morey, 2010). We also included a larger set of stimuli in the final experiment as compared with Experiments 1 and 2. Our rationale for using a larger pool was that the stimuli would be presented less frequently over the course of the experiment compared with

Experiments 1 and 2. This would prevent participants from becoming overly familiar with the to-be-remembered items and reduce the likelihood that participants would develop their own verbal labels that could be rehearsed. Congruent with the first experiment, there were also no differences in level of motivation to score points, level of tiredness, or overall motivation devoted to the task as a function of the between-participant reward manipulation.

Experiment 3: Unfamiliar characters

Response time Participants responded to the red list positions in the high-reward condition more quickly than they did control probes, and, again, this pattern is not evident for red list positions in the equal-reward condition (see Fig. 2c). This pattern was statistically supported by a three-way interaction, $F(6, 384) = 10.93$, $\eta_p^2 = .15$, $BF = 7.11 \times 10^6$, in favor of an effect. Bayes Factor *t* tests comparisons favored an effect of shorter RTs for prioritized positions (red items) compared with control items in the same probe position for the high-

Fig. 4 Proportion of participants endorsing different working memory maintenance strategies as a function of experimental condition in Experiments 1–3

Table 2 Subjective ratings for level of motivation to score points, level of tiredness/fatigue, or overall motivation for all experiments as a function of the point value manipulation

		N	How motivated were you to score a high number of points?		How tired were you while performing the experiment?		Overall, how motivated were you throughout the experiment?	
			M (SD)	BF	M (SD)	BF	M (SD)	BF
Experiment 1	Equal reward	33	83.5 (18.5)	.28	56.1 (30.8)	.27	69.2 (22.6)	.27
	High reward	29	81.5 (20.6)		54.4 (30.8)		68.6 (20.5)	
Experiment 2	Equal reward	29	82.3 (15.9)	.27	58.2 (21.7)	.31	66.5 (18.5)	.37
	High reward	30	81.1 (18.8)		53.7 (31.0)		71.3 (23.1)	
Experiment 3	Equal reward	36	79.6 (18.5)	.25	53.7 (32.3)	.26	66.5 (21.3)	.27
	High reward	30	79.3 (16.0)		55.1 (24.9)		67.5 (19.0)	

Note. All ratings were made using a continuous slider with anchors of 0 (*not at all*) to 100 (*extremely*). A few participants did not provide ratings for all subjective questions (3% of all responses) and were not included in the analysis

reward condition for Probe Position 1, $t(29) = 4.70$, $BF = 424$; Probe Position 2, $t(29) = 3.53$, $BF = 25$, and Probe Position 3, $t(29) = 2.81$, $BF = 5$. This pattern was not observed in the equal-reward condition, where red positions did not produce any evidence of differing from control positions (all $BFs < 1$).

Accuracy There was strong evidence for a three-way interaction between all three manipulations, $F(6, 384) = 7.93$, $\eta_p^2 = .11$, $BF = 1.26 \times 10^5$ (see Fig. 3c). Analysis of the individual comparisons show more accurate responses for prioritized positions compared with control positions in the high-reward condition for Probe Position 1, $t(29) = 3.25$, $BF = 13$, and Probe Position 2, $t(29) = 3.07$, $BF = 9$, but ambiguous evidence for a difference at Probe Position 3, $t(29) = 1.96$, $BF = 1$. Accuracy for prioritized positions showed no evidence of differing from the control positions in the same serial position under the equal-reward condition (all $BFs \leq 1$).

Posttask questionnaire The unfamiliar character stimuli used in Experiment 3 led to only 5% (high-reward $N = 2$; equal-reward $N = 1$) of participants reporting use of a rehearsal strategy (see Fig. 4). There was also no evidence for a difference between groups in motivation to score points, level of tiredness, and overall motivation (all $BFs < 1$; see Table 2).

Discussion In line with the first two experiments, the RT data from Experiment 3 support the flexible-attention theory over the distinctiveness of encoding theory. Similar patterns were evident in accuracy. The data from Experiment 3 also decisively rule out a contribution of rehearsal to prioritization effects in visual working memory. Only a minority of participants selected rehearsal as a strategy they used to help remember the information. Yet the same pattern of prioritization effects was observed as in previous experiments. Corroborating the preceding experiments, motivation and tiredness/fatigue do not explain between group differences.

Next, we further unpack the role of rehearsal in a post hoc analysis by comparing RT differences between participants who used rehearsal with participants who reported using alternative strategies that differed from rehearsal.

Combined analysis across experiments

Rehearsal versus alternative strategy We collapsed data across all three experiments and classified participants as either using or not using a rehearsal strategy based on posttask questionnaire responses to further evaluate the role of rehearsal in flexible resource allocation. As our main inferential interest is retrieval speed from working memory, we focus on RT for this analysis. We included strategy use (rehearsal vs. alternative strategy) as a between-participants factor in a 2 (strategy use) $\times$ 4 (prioritization position) $\times$ 3 (probed position) mixed ANOVA. Given clear evidence against the distinctiveness explanation from the RT analysis, we restricted this analysis to RTs for participants who were randomized into the high-reward condition. While inspection of the mean RT as a function of condition (see Fig. 5) showed longer RTs for participants who reported using a rehearsal strategy, this pattern was not statistically supported. There was evidence against the presence of three-way interaction for strategy use, $F(1, 87) = 2.41$, $\eta_p^2 = .03$, $BF = .05$.

Resource allocation To understand how resources were distributed within the focus of attention we compared RTs for the prioritized list against RTs for the final list position (recency) from the same list. These analyses were also restricted to the high-reward condition and collapsed across all experiments (see Fig. 6). When Serial Position 1 was prioritized, RTs were invariant compared with the last item (recency) from the same list, $t(88) = .43$, $BF = .13$. The same pattern was evident when Serial Position 2 was prioritized and compared with the last item, $t(88) = .63$, $BF = .14$. We also evaluated whether

Fig. 5 Response-time data collapsed across all three experiments and compares participants from the high-reward condition who did not use a rehearsal strategy (alternative strategy) with participants who used a rehearsal strategy. The red colored bars represent the list positions

prioritized to in red, and the black colored bars represent the control list positions. Labels on the x-axis (SP 1 Red, etc.) correspond to trials with matching the label in Fig. 1. Numerical values (1, 2, 3) above the x-axis labels indicate probed serial position. SP = serial position

flexibility and the benefit of orienting attention and prioritizing a list position came at the expense of performance on the last item in the list by comparing the final item when another list position was prioritized against the final item in the control condition when no list positions were prioritized. When Serial Position 1 was the prioritized red item, the retrieval speed for

the last item (recency) from the same list was longer than the last item (recency) in the control condition, $t(88) = 4.14$, $BF = 239$. This same pattern was evident for the last item in the list when serial position two was the prioritized red item, $t(88) = 3.68$, $BF = 53$.

Fig. 6 Response-time data collapsed across all three experiments and collapsed across strategy use from the high-reward condition only. The red colored bars represent the list positions prioritized to in red, and the black colored bars represent the control list positions. Labels on the x-axis (SP 1 Red, etc.) correspond to trials with the matching label in Fig. 1. Numerical values (1, 2, 3) above the x-axis labels indicate probed serial position. SP = serial position

General discussion

We contrasted a flexible-attention theory against a distinctiveness of encoding theory to better understand item priority effects on the focus of attention. Findings across three experiments provide converging support for the flexible-attention theory and clear evidence against the distinctiveness of encoding theory. Shorter RTs for prioritized high-reward items are indicative of more rapid access to these items from within the focus of attention. Participants flexibly adjusted their attention to prioritize these items when a single feature indicated they were worth more points than other items in the list. Improved performance was not observed when points were held constant across list positions, ruling out the distinctiveness of encoding explanation, and similar patterns are evident in the accuracy data. When the stimulus materials were unfamiliar characters (Experiment 3), the majority of participants reporting using nonrehearsal strategies in agreement with other research that rehearsal is not an adequate explanation for flexibility (Sandry et al., 2014). This also provides strong evidence for the previously untested assumption that unfamiliar characters reduce the likelihood of using a rehearsal strategy (Ricker & Cowan, 2014). Because the evidence does not support differential motivation or differential tiredness/fatigue as a function of the reward manipulation,

we can also rule out these as plausible explanations for the observed flexibility in the prioritization effect. These data simultaneously demonstrate that the ability to flexibly adjust the focus of attention extends to sequentially presented visual memoranda.

Reward, strategy, and motivation

One way that reward improves cognitive processing is by modulating cognitive control via an indirect effect of increased motivation (Botvinick & Braver, 2015). Motivation may improve memory in particular by causing participants to use a rehearsal strategy (R. C. Atkinson & Wickens, 1971; Eysenck & Eysenck, 1980, 1982). Understanding strategy use on the posttask questionnaire is important because a successful rehearsal strategy applied in the present paradigm could mimic the effects of flexible attention directed toward specific items. In Experiments 1 and 2, a large proportion of participants who completed the study reported using a rehearsal strategy to help remember the information. It is possible that these participants assigned a verbal label to the stimulus materials and rehearsed that label over the course of the experimental session. This could heighten the ease of accessibility for the rehearsed item and decrease RTs, possibly interacting with the reward manipulation.

The unfamiliar characters used in Experiment 3 nearly eliminated participants reporting the use of a rehearsal strategy, yet we still found a robust effect of attentional flexibility within the focus of attention. Importantly, across all experiments, the proportions of participants who reported using a rehearsal strategy in the equal-reward condition (.29) was nearly the same as the proportion of participants who reported using a rehearsal strategy in the high-reward condition (.31). This suggests that the reward manipulation did not meaningfully increase reliance on rehearsal strategies used in the high-reward condition compared with the equal-reward condition. This is congruent with neuroimaging evidence showing reward does not increase activation in brain regions ostensibly related to rehearsal during a sequentially presented verbal working memory task (Gilbert & Fiez, 2004).

In follow-up analyses, we compared performance between participants who reported using a rehearsal strategy with participants who reported using an alternative strategy, specifically for the high-reward condition. The findings from that post hoc analysis also support the flexible-attention theory. Regardless of the strategy participants reported using, there was a clear effect whereby prioritized probes were retrieved more quickly than were control probes. These data also support our earlier work where we included an articulatory suppression condition to block subvocalization and found a robust effect of flexibility in the focus of attention (Sandry et al., 2014).

It is unlikely that participants would use a grouping or chunking strategy (Chen & Cowan, 2005; Cowan, Chen, & Rouder, 2004) that would contribute to the prioritization effect; however, this assumption has never been directly tested. The rationale is that the rapid presentation speed of the stimuli would reduce the likelihood that participants would rely on grouping or chunking (Nee & Jonides, 2008, 2011). Additionally, grouping typically occurs when stimuli are from common categories (McElree, 1998) or there are temporal boundaries that can delineate the novel formation of chunks (Hitch, Burgess, Towse, & Culpin, 1996). Neither of these variables were introduced in the current investigation. The posttask questionnaire provides credibility for this assumption. Across all three experiments, only 5% of participants endorsed using a grouping strategy (equal-reward $N = 4$; high-reward $N = 5$).

One additional effect that high reward has on cognitive performance is counteracting the negative effects of tiredness/fatigue. In conditions of high reward, participants will exert more cognitive effort and remain engaged on the task for longer periods of time (Boksem & Tops, 2008; Dobryakova et al., 2013). This can lead to performance improvements compared with conditions of low reward that impair performance (Boksem & Tops, 2008). We evaluated the possibility that the high-reward condition in the current research led to changes in tiredness/fatigue. There were no differences on the posttask question asking “How tired were you while performing the experiment?”, making it unlikely that tiredness/fatigue account for the current findings. Consistent with tiredness/fatigue providing a poor explanation for the effect, general motivation did not account well for the present findings, either. There were no differences on the posttask questionnaire for either of the motivation questions. Taken together, indirect effects of increased motivation, including differential strategy use, and increases or decreases in tiredness/fatigue are inadequate explanations for attentional flexibility and prioritization within working memory and the focus of attention.

Maintenance mechanism

These data largely rule out distinctiveness of encoding as an adequate explanation for attentional flexibility and prioritization. The findings from the posttask questionnaire also minimize the likelihood that participants used a rehearsal strategy and do not support the presence of reward changing participants’ overall motivation or tiredness/fatigue. One plausible mechanism that would allow the focus of attention to flexibly maintain non-recent information in a prioritized state is attentional refreshing. Attentional refreshing, the domain general (Vergauwe, Barrouillet, & Camos, 2010) process of applying attention to keep memoranda in an active state (Barrouillet, Bernardin, & Camos, 2004; Camos, Johnson, et al., 2018a;

Cowan, 1988; Johnson, 1992; Raye, Johnson, Mitchell, Reeder, & Greene, 2002), is a developing mechanistic explanation for many working memory observations, including maintenance of nonverbal information (Vergauwe, Camos, & Barrouillet, 2014). Many studies of attentional refreshing assume the memory trace is reactivated through a covert retrieval process. Typically, in a reactivation paradigm, items are presented, and one item is retrospectively cued after a brief interval to indicate to participants which items may be relevant for an upcoming decision (Griffin & Nobre, 2003; Landman, Spekrijse, & Lamme, 2003; Oberauer, 2001; Souza & Oberauer, 2016). In these paradigms, the displaced information will reenter the focus of attention from a less active state (but see Souza, Rerko, & Oberauer, 2016, for an alternative removal account).

If the present prioritization effect is due to attentional refreshing, the present findings make salient the question, Did the prioritized item remain active in the focus of attention over the course of the trial, or did the prioritized item become reactivated when it was probed? For example, when the first serial position was prioritized to in red, did it remain in a high state of activation while the second and third serial positions were subsequently presented, implying the first serial position never left the focus of attention? If the prioritized position did remain active in this fashion, this suggests that refreshing can operate not only through reactivation in the retrocue sense but also in an always active or *online* state. This online refreshing view is congruent with the seminal studies investigating refreshing under the context of the Multiple-Entry, Modular Memory System framework (Johnson, 1992). These investigations operationalized refreshing as “keeping information active so that it might be easily used” (Johnson, 1992, p. 274) or a mental operation that “prolongs activation of just-activated representations” (Johnson, Reeder, Raye & Mitchell, 2002 p. 64).

When interpreting flexible attention prioritization observed in the present research, refreshing (especially *online* refreshing) is a parsimonious explanation for the effect. Online refreshing may manifest as a proportion of attentional resources being continuously directed toward the prioritized item, with the remaining attentional resources directed to new, subsequently presented information. In this view, the prioritized item never leaves the focus of attention. Determining how flexible-attention allocation maintains the prioritized representation may have implications for understanding working memory capacity limits, which we describe in more detail in the next section.

Some prior research is at odds with the attentional refreshing interpretation. Specifically, unfamiliar characters (Ricker & Cowan, 2010) and unfamiliar fonts (Vergauwe et al., 2014), like those in the present research, may not be able to be refreshed. This may be because there is not a preexisting long-term memory representation for unfamiliar information.

This interpretation, that refreshing cannot operate on temporary or perceptual representations, does not accord well with a refreshing explanation for the present research. Our present data suggest that the conclusion from these earlier investigations—that there is no refreshing for unfamiliar information—may be incorrect or alternatively, prioritization effects might depend on some other process besides attentional refreshing.

Recent verbal memory research supports the refreshing account for the prioritization effect observed in the present research. In a series of experiments, word frequency and lexicality effects that commonly influence long-term memory did not interact with or influence attentional refreshing, suggesting the processes may be independent (Camos, Mora, et al., 2018b). This is incongruent with the assumption that refreshing will not occur if there is not a preexisting, long-term memory representation (Ricker & Cowan, 2010; Vergauwe et al., 2014). It does not rule out that the nature of the stimulus material, familiar versus unfamiliar information, interacts with refreshing and dependence on long-term memory.

The Camos, Mora, et al. (2018b) verbal memory findings, demonstrating that refreshing does not depend on long-term memory, are congruent with our earlier suggestion that refreshing may operate on early consolidation processes (Sandry et al., 2014). In that theoretical view, refreshing that results from prioritization may help to stabilize the memory trace by encouraging tetanic firing, leading to more efficient long-term potentiation at the neuromolecular level of the synapse (Bliss & Collingridge, 1993; Bliss & Lømo, 1973) during the early process of cellular consolidation (Dudai, 2004; Genzel & Wixted, 2017; Wixted & Cai, 2013). Prioritization may strengthen the short-term consolidation process (Ricker, Nieuwenstein, Bayliss, & Barrouillet, 2018) by flexibly maintaining attention on the prioritized item over the course of the trial (always active, online refreshing). Prioritization might also act on short-term consolidation processes by buffering the prioritized list position against mask-related interference or the slowing of short-term consolidation that occurs at mask onset (Ricker & Sandry, 2018). In a recent study using the same paradigm as the present research, we found that prioritizing information in working memory led to a related performance boost in long-term memory (Sandry, Zuppichini, & Ricker, 2020). Congruent with prioritization acting on consolidation, prioritizing information in working memory may also strengthen consolidation into long-term memory.

Resource distribution in the focus of attention

The present data provide additional insight into how resources are distributed within the focus of attention. In the *resources allocation analysis*, we collapsed across experiments for the high-reward condition and found an invariance in retrieval speed for the prioritized positions compared with the recency

position from the same list. There was a standard recency advantage in the control condition with no red items in the list. There was a small but evident recency advantage *along with* a prioritization effect in conditions with a red item in the list, and these two list positions (recency and prioritization) did not statistically differ from each other. This invariance supports models of working memory with a multiitem focus of attention (Cowan, 1988, 2001, 2005; Portrat & Lemaire, 2015) and implies that the focus of attention can accommodate at least two items (Beck & Hollingworth, 2017; Beck, Hollingworth, & Luck, 2012; Gilchrist & Cowan, 2011; Grubert & Eimer, 2015; Hollingworth & Beck, 2016). It is also possible that this pattern reflects aggregating of data across trials. That is, high-priority items and recency may have been more likely to be held within the focus of attention in comparison with equal reward items, but not on the same trial. Similar investigations into the prioritization effect may suffer from this same limitation (Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2014). This finding differs from our earlier research where we reported a retrieval speed advantage for the prioritized item over and above the recency effect (Sandry et al., 2014). In Sandry et al. (2014), retrieval speed for recency was significantly reduced compared with retrieval speed for the prioritized list position. The main difference between these investigations is that the earlier research used single-letter verbal stimuli, whereas the present research used visual objects. The type of stimulus material, verbal versus visual, or level of stimulus familiarity may determine whether we maintain one or more item within the focus of attention, especially as it relates to flexible resource allocation in working memory. The disparate pattern across materials supports models where the focus of attention is assumed to be a flexible resource that can zoom in and zoom out, depending on task demands (Cowan et al., 2005; Eriksen & St James, 1986; Oberauer & Hein, 2012; Sandry et al., 2014).

One additional finding from the *resources analysis* is that when the first or middle serial position was prioritized, retrieval speed for the most recent position from that list slowed. This is in line with earlier findings (Morrison et al., 2014; Sandry et al., 2014) and suggests that there is a resource trade-off associated with prioritization and attentional flexibility. This is also congruent with models that assume working memory resources are limited (Zhang & Luck, 2008), but capable of being distributed flexibly across the content of working memory (Fallon, Zokaei, & Husain, 2016). When attention is allocated to earlier list positions, flexible prioritization effects come at a cost to recency. In at least one case prioritization has resulted in little to no resource trade-off, but the paradigm used was quite different from other studies. Myers, Chekroud, Stokes, and Nobre (2017) cued multiple items as high-priority with a retrocue that included information about probe order and found strong attenuation of the resource

trade-off. Whether this finding is replicable outside of the specific conditions investigated is an open question.

A parallel line of research investigating prioritization effects and interference shows a comparable resource trade-off as in the present study. By similarly manipulating the point structure associated with to-be-remembered items, behavioral performance for the high-reward item improves but this comes at the expense of the other memoranda. The prioritized item is also more susceptible to interference from a poststimulus suffix (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014). This interference finding is particularly interesting given other research demonstrates that reward-related processing in working memory is less susceptible to interference when task parameters do not require updating (Fallon & Cools, 2014).

The disparate findings related to interference, reward, and prioritization may be at least partially due to paradigmatic differences across studies. Interference effects are observed when information about the reward precedes the encoding trial. Interference effects are not observed when information about the reward follows initial encoding. Reward that precedes encoding may cause participants to flexibly maintain their attention on the prioritized representation. In this instance, the prioritized representation may never leave the focus of attention over the course of the trial—an assumption in line with the *online refreshing* interpretation described earlier. When participants prepare for a trial and they expect a reward, reward-related attentional prioritization may delay the transformation of the stimulus into a working memory representation, leaving it within focal attention and leaving it more susceptible to interference. This interpretation aligns well with evidence that suggests the contents of the focus of attention are susceptible to interference (Beaudry, Neath, Surprenant, & Tehan, 2014; Carroll et al., 2010; Ralph et al., 2011). Given the reward precedes the encoding trial in the current research, the prioritized list position in this paradigm may be susceptible to interference effects. This is similar to studies investigating the interaction between prioritization and suffix effects (Hitch et al., 2018; Hu et al., 2016; Hu et al., 2014). This hypothesis should be directly evaluated in future research in order to begin to understand what happens to a prioritized representation over the course of a trial, and how an iconic memory is transformed into a working memory representations. These future directions will be useful in understanding how attentional flexibility and prioritization operate within working memory.

Reward-based modulation of attention

The literature on value-driven attentional selection shows that reward modulates attentional control (Anderson, 2013; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Failing & Theeuwes, 2018) and indirectly affects representations held in visual working memory (Gong & Li, 2014). In these

paradigms, stimulus–reward associations are first learned over the course of a training phase, and those learned associations increase attentional capture of task-relevant targets and irrelevant distractors on a subsequent, unrelated exogenous attention task (Anderson, Laurent, & Yantis, 2011). Value-driven attentional selection is likely an independent mechanism from the traditional bottom-up/top-down attentional dichotomy (Awh, Belopolsky, & Theeuwes, 2012). While the effects are similar, it seems reasonable that the prioritization effect reported here may be governed at least in part by top-down attentional control because participants were specifically instructed about the purpose of the reward, and there was no initial learning trial. One main difference between the top-down prioritization manipulation used here and value-driven attentional effects is that value-driven attentional selection may rely more heavily on long-term memory, given the stimulus–reward bindings formed over the initial learning/training period are necessary to see the effect on the subsequent task.

Extensions of the value-based selection literature to visual working memory demonstrate that previously learned stimulus–reward associations also improve working memory encoding (Wallis, Stokes, Arnold, & Nobre, 2015) and modulate working memory maintenance processes (Thomas, FitzGibbon, & Raymond, 2016). It is unclear how prioritization in the current paradigm maps onto entry into, or maintenance of, representations in working memory because the designs differ considerably. Crucially, the present work does not incorporate an initial learning phase, and the reward is task relevant. Future research will be necessary to identify which working memory processes are affected by task-relevant reward-related prioritization. Moreover, additional research is necessary to identify whether a similar effect would emerge if the present paradigm was modified to use an initial learning phase to build stimulus–reward associations. Because working memory is affected by value-directed attention (Thomas et al., 2016; Wallis et al., 2015), we do anticipate a comparable finding with the one we report here. If that carryover is observed in future research, then it implies a role for reward or selection history along with top-down guidance of attention for task-relevant prioritization. While these are open questions, there are some theoretical views of how attention is represented neurally, as a priority map, that may help explain the current findings.

The concept of a priority map assumes that continuously updating outside signals are represented across a large neural network. The areas on the priority map that are the most active will guide spatial attention by directing it toward the representation with the highest priority signal (i.e., the highest peak on the map; Failing & Theeuwes, 2018; Fecteau & Munoz, 2006). Along with input from top-down and bottom-up processes and congruent with the tripartite model of attention (Awh et al., 2012), reward signals can also contribute to neural

activation on the priority map and further bias the allocation of attention (Chelazzi et al., 2014). While spatial priority maps are assumed to represent the external visual world, a similar priority map may be useful in describing the present findings and endogenous attention allocation. If the focus of attention operates like or depends on a priority map, then a high-reward serial position would bias attention, with those positions receiving the highest priority signal. The priority map theory may explain how online refreshing and the focus of attention selects information within working memory.

The neurons that represent prioritized serial positions (red high-reward items) may remain at a continuous high level of activation with corresponding continuous high activation on the priority map over the course of the sequential probe-recognition trial. In comparison, neurons that represent serial positions that are not prioritized (black equal-reward items) may decrease in activation with a similar decrease in activation on the priority map. When tested on the choice screen, the prioritized items and their corresponding highly active neural representation on the priority map would be at an advantage in comparison with less active nonprioritized items. This would result in the pattern we report here of short RTs and high accuracy for the prioritized representation. The resource trade-off that we observed in the present research can be similarly understood under a priority map framework. When limited attentional resources are flexibly maintained on prioritized representations, this would result in a resource shift across the priority map. Some of the available resources that would typically be directed to nonprioritized representations would be redirected to prioritized representations, reflected as the highest peak on the map. There is additional evidence that may support neural overlap between the priority map framework of attentional selection and the focus of attention.

Among other brain regions, the intraparietal sulcus (IPS) is an important brain area involved in visual working memory capacity (Todd & Marois, 2004; Xu & Chun, 2006) that specifically corresponds to representations that are held in the focus of attention (Cowan, 2011; Majerus et al., 2007). The role of the IPS in working memory is robust regardless of stimulus modality (Cowan et al., 2011). Intraparietal areas are also implicated as important brain regions related to attentional selection and priority maps (Bisley & Goldberg, 2010). Spatial attention and spatial working memory show interacting patterns of task-related activation in the IPS (Silk, Bellgrove, Wrafter, Mattingley, & Cunnington, 2010), and some evidence suggests attentional selection-related activation in the IPS is not dissociable from working memory-related activation in the IPS (Gillebert et al., 2012). The IPS may be a critical area involved in representing information that currently occupies our attention, regardless of whether it is exogenous or endogenous.

The common source hypothesis is another possible explanation for a relationship between priority maps and working

memory. This view suggests that top-down goal states in visual working memory contribute to constructing a priority map (Zelinsky & Bisley, 2015). The relationship between working memory and priority maps may be recursive or symbiotic in nature if all attention including the focus of attention depends on shared neural resources associated with a single priority map. Alternatively, there may be multiple neural instantiations of priority maps depending on whether attention is internal (focus of attention) or external.

Limitations

The set size used in the present research was small and only used three items. This was intentional to match the paradigm used in our earlier research and remain within the capacity limit of working memory. It is possible that three items are not adequate to illicit the isolation effects of the von Restorff effect. For example, it is possible that the distinct item did not pop out when presented in serial position one. As a comparison, spatially isolated items from a simultaneously presented array show a traditional von Restorff effect for large, but not small, set sizes when evaluated using an old/new recognition memory paradigm (Morin, DeRosa, & Ulm, 1967). In subsequent research, it will be informative to contrast the flexible attention theory against the distinctiveness of encoding theory using larger set sizes of sequentially presented information, thus eliciting a stronger pop-out effect. A larger list of items may also be informative for if and how prioritization operates when the set size exceeds working memory capacity. It should be noted that we did observe prioritization effects in the present work. Given the presence of the prioritization effect here, any explanation of the present data as not conducive to producing a von Restorff effect necessarily argues that the prioritization effect results from flexible attention and not distinctiveness of encoding.

The strategy questionnaire completed at the end of the study asked participants to reflect on the entire experiment and select the strategy that best described how they remembered the shapes/arrows/symbols. It is possible that participants modified the strategy that they used over the course of the experiment or depending on the type of trial. For example, participants may have adopted one type of strategy when there was a red letter in the list and then adjusted and adopted an alternative strategy for the all black trials. Further, some participants may have used an assortment of strategies across the entire testing session. The participant responses to the questions regarding strategy use may reflect the most common strategy that they applied, their most recent strategy, or their most effective strategy. Along these same lines, the specific use of rehearsal may have changed between the reward conditions. That is, participants in the high-reward condition may have rehearsed the high-reward item while participants in the equal-reward condition may have rehearsed all list items.

The findings from Experiment 3 and the rehearsal versus alternative strategy analysis are difficult to reconcile with this alternative interpretation of the present findings. In Experiment 3, the pattern of results was the same as in the previous experiments, despite a near complete lack of rehearsal by the participants. This makes explanations of our findings based upon changes in rehearsal patterns problematic. These limitations are inherent when asking for self-reported strategy use at the end of the experiment. In future research, it will be valuable to understand whether participants adopt difference strategies depending on condition or trial by asking about strategy use immediately after some percentage of trials. The other questions on the posttask questionnaire share similar self-report limitations.

Conclusion

Over a series of three experiments, we found strong support for an attentional-flexibility account of prioritization effects within the focus of attention. Feature distinctiveness alone could not account for the benefit of cueing an item as high reward with a visual-feature cue, in conflict with predictions from the distinctiveness of encoding theory. Additional evidence rules out differential use of rehearsal strategies, motivation and tiredness/fatigue as reasonable mechanistic explanations for the findings. Instead, the results strongly support an attentional flexibility account that is parsimoniously attributed to an online attentional refreshing process. Participants are able to maintain nonrecent visual information that is sequentially presented in a state of heightened accessibility when encouraged by task demands. This special status comes at a cost to other information in the form of a resource trade-off, supporting a finite working memory capacity resource that can be flexibly distributed.

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Open practices statement The data for all experiments are available here: <https://osf.io/hdvjp/>

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