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RESEARCH ARTICLE

Eyes wide open: enhanced pupil dilation when selectively studying important information

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Abstract Remembering important information is imperative for efficient memory performance, but it is unclear how we encode important information. The current experiment evaluated two non-exclusive hypotheses for how learners selectively encode important information at the expense of less important information (differential resource allocation and information reduction). To evaluate these hypotheses, we measured changes in learners' pupil diameter and fixation durations while participants performed a selectivity task that involved studying lists consisting of words associated with different point values. Participants were instructed to maximize their score on a free recall task that they completed after studying each list. Participants' pupils dilated more when studying high-valued than low-valued words, and these changes were associated with better memory for high-valued words. However, participants fixated equally on words regardless of their value, which is inconsistent with the information reduction hypothesis. Participants also increased their memory selectivity across lists, but changes in pupil diameter and differences in fixations could not account for this increased selectivity. The results suggest that learners allocate attention differently to items as a function of their value, and that multiple processes and operations contribute to value-directed remembering.

Keywords Selective encoding · Pupil dilation · Attention · Value-directed remembering · Metacognition

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Introduction

The information that people encounter everyday varies in value—or importance—for remembering. People must be able to selectively encode and later retrieve valuable information to function efficiently. The process of "value-directed remembering" (see Castel 2008) involves selectively attending to and recalling high-value information relative to lower-value information. Though people typically have better memory for high- than low-valued information, the processes that contribute to value-directed remembering are not well understood (Ariel et al. 2009; Castel et al. 2002; Kahneman and Peavler 1969; Weiner and Walker 1966; Heyer and O'Kelly 1949). Specifically, it is unclear how people encode high-valued information differently than low-valued information. Candidate mechanisms include attentional control and the strategic allocation of cognitive resources. In the current experiment, we evaluated two non-exclusive hypotheses for why people have better memory for high- than low-valued information. We refer to these hypotheses as the differential resource allocation hypothesis and the information reduction hypotheses.

The differential resource allocation hypothesis claims that people allocate more attentional resources when encoding high- than low-valued items, while the information reduction hypothesis claims that people strategically ignore encoding low-valued items because they are not important to remember. Both hypotheses offer attentional explanations for why learners have better memory for high- than low-valued items. However, each hypothesis provides a distinct explanation for the memorial benefits that occur for valuable information. The former argues learners attempt to encode both high- and low-value items, but they allocate more attention to learning high-valued relative to low-valued items. The latter argues that the memorial benefits of item value stem entirely from avoiding low-valued items during study. Consider how these hypotheses may contribute to value-directed remembering in a memory selectivity task. In a selectivity task (e.g., Castel et al. 2002; Watkins and Bloom 1999), participants study lists of words and each word is paired with point values ranging from 1 to 12. Each point value indicates how important that word is to remember and participants are instructed that they will receive a word's point value for recalling it after the presentation of each list. Participants are instructed to remember as many words as possible and to maximize their score on each test. After each test, participants are given feedback about their score and instructed to increase their score on the next list.

The results from a selectivity task typically yield several findings. First, participants typically recall a similar number of words within each list indicating that their memory capacity is relatively consistent across the task. Second, the number of high-valued words they recall is usually greater in later lists than earlier lists suggesting that they learn to selectively encode high-valued words through task experience. Third, participants with attentional deficits such as low working memory spans or attention deficit hyperactivity disorder display impairments in the selective encoding and retrieval of high-valued information (Castel et al. 2009, 2011; Hayes et al. 2013). This latter finding suggests that attentional control processes may play an important role in memory selectivity. However, exactly how attentional processes are used to selectively encode high-valued items is unclear, and it is difficult to directly measure how people allocate attention to information that differs in value.

Although it is difficult to directly measure differences in attention allocation, it can be inferred by examining task-evoked pupillary responses (TEPRs) during study (Bijleveld et al. 2009; Kahneman 1973; Kahneman and Peavler 1969). People's pupils dilate during cognitively demanding tasks (Beatty 1982; Karatekin et al. 2004). Fluctuations in pupil diameter closely mirror event-related activity in the locus coeruleus (Gilzenrat et al. 2010), a norepinephrine regulating system that plays a key role in attentional control (Aston-Jones and Cohen 2005). Thus, TEPRs can be used to measure phasic changes in attention allocation (for a review, see Goldinger and Papesh 2012), and can shed light on how attention may be allocated when studying information varying in value.

Fixation locations and fixation durations during reading can also provide insights into attention allocation and processing status for words during study. Fixations provide a measure of moment-to-moment attention allocation during reading (Just and Carpenter 1980; Rayner 1998; Rayner and Liversedge 2004). During normal reading, people typically fixate on words between 200 and 250 ms and lexical activation for a word typically occurs between 100 and 200 ms post-fixation (Sereno and Rayner 2003; Sereno et al. 1998). Given the timing constraints of a normal fixation during reading, one can assume that fixation durations beyond 250 ms in a memory selectivity task likely reflect post-lexical processes aimed at encoding words.

In the current experiment, participants performed a selectivity task, and we computed TEPRs during the presentation of each word-point value pair during study. If learners allocate resources differently to encode high- and low-valued words, then TEPRs should increase with item value during the selectivity task. Furthermore, if differential resource allocation can account for the improved memory for high-valued items that participants typically display as they gain task experience, difference in TEPRs between high- and low-valued words should increase as memory selectivity increases across lists. Second, to evaluate the information reduction hypothesis, we examined fixation duration on words and their value. If learners ignore low-valued words, then they should never (or rarely) fixate on words that are paired with a low value or they should only fixate very briefly (~250 ms or less), in order to read the word and its value, but not engage in encoding of the word itself. Moreover, if information reduction results in increased memory selectivity across lists, then fixation duration for low-valued items should decrease across lists. Of course the results could support both hypotheses because they are not mutually exclusive. People may differentially allocate their attention to words as a function of their value and choose to ignore the lowest-valued words during study. If so, people may choose to not study and hence never fixate on the lowest-valued words. However, their TEPRs will differ for the higher- versus lower-valued words that are fixated.

Method

Participants, materials, and apparatus

Forty-seven undergraduates from Kent State University participated for course credit. Pupil diameters were recorded using an ASL D6 desk-mounted optics remote eye tracker unit sampling at 120 Hz. The task was programmed using E-prime software. All words were presented in white Courier New 36-point font, on a black background on a 16 × 10 monitor. The words in each list were concrete monosyllable nouns containing 5 letters (e.g., truck) and were similar in frequency. The mean hyperspace analog to language (HAL) frequency of the words was 7,240 (Log HAL = 8.77), obtained from the elexicon.wustl.edu Web site (Balota et al. 2007). Words were randomly sorted into 8 lists of 12 words. Words in each list were assigned a unique point value between 1 and 12, and across lists words were arranged so that a different point value appeared in each serial position to ensure that value was equally distributed across serial positions. The mean value of each word for each serial position ranged from 6.2 to 6.8.

Procedure

Participants were placed in a chin rest approximately 22 inches (~56 cm) from the computer screen and calibrated on the eye tracker. After calibration, participants began the selectivity task. They were instructed that they would be studying lists of words paired with point values ranging from 1 to 12 and they would earn points for recalling each word. They were told that their goal was to get as many points as possible and the best way to maximize their score on each list was to remember as many of the high point value words as they could. They were given instructions and an example describing the scoring procedure of the experiment. They were instructed that after the presentation of each list, they would see the word "RECALL" and at this point they would recall out loud as many words as they could remember and they would earn the points associated with these words. Each list consisted of 12 trials. On each trial, participants first viewed a fixation cross for 1,500 ms, which was followed by a 50-ms delay. Next, a word and its point value (e.g., truck 8) were presented for study for 2,000 ms. The word was presented to the left of the fixation cross location and the value was presented to the right. The study presentation was followed by a 50-ms delay. After 12 trials, the word "RECALL" was presented and participants recalled aloud any words that they could remember. After recall, feedback was given on the number of words correctly recalled and the number of points earned. Participants then proceeded to study the next list of words. The experiment continued until participants finished all 8 lists.

Results

To simplify and reduce noise in the analyses, we collapsed the point values into three categories: low-value (1–4 points), medium-value (5–8 points), and high-value words (9–12 points). Previous research suggests that these categories accurately reflect people's perceptions of what constitutes low-, medium-, and high-valued pairs because their performance often differs across these categories but is somewhat similar within each (see Castel 2008).

Recall and selectivity

The proportion of words recalled and the average memory selectivity for each list is presented in Fig. 1. Memory selectivity was evaluated by computing a selectivity index

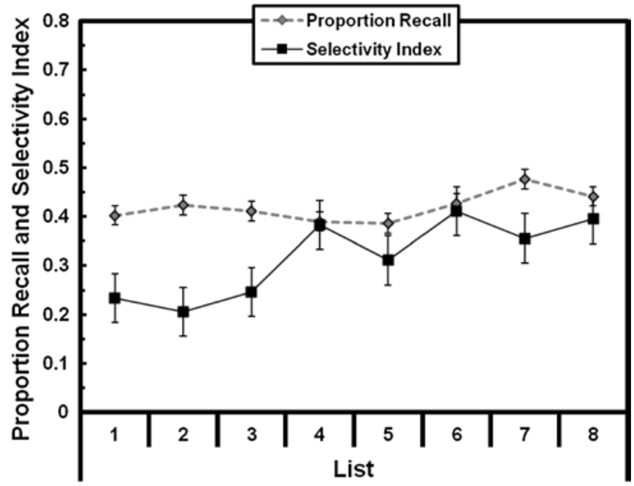

Fig. 1 Mean proportion recall and mean selectivity index (SI) across lists. *Error bars* represent within-subject standard error of the mean (Loftus and Masson 1994)

(SI) using the following equation developed by Watkins and Bloom (1999; see also Castel et al. 2002; Hanten et al. 2007).

$$\text{Selectivity index (SI)} = \frac{\text{Total points earned} + (\text{chance score} \times \text{total words recalled})}{\text{ideal score} + (\text{chance score} \times \text{total words recalled})}$$

The SI measures a participant's score relative to a chance score and an ideal score. For example, if a participant remembered four words worth 12, 10, 9, and 8 points, that participant's SI would be considered quite high. The ideal score for four words is 12 + 11 + 10 + 9 = 42, whereas the participant's score is 39. A chance score involves calculating the average points earned (using a 12-word list, the average would be 6.5) and multiplying that value by the number of words recalled. Thus, the SI in this case is (39 + 26)/(42 + 26) = .96. The SI yields values ranging from 1 to −1, where 1 indicates recall of only the highest-valued words and a −1 indicates recall for only the lowest-valued. Values close to zero indicate memory is not sensitive to value.

Figure 1 shows that the proportion of words recalled was relatively consistent across lists, while memory selectivity was higher in later lists than earlier lists. Repeated-measures ANOVAs revealed an effect for list on both recall, $F(7,40) = 2.35$, MSE = 5.97, $p < .05$, $\eta_p^2 = .29$, and SI, $F(7,40) = 2.38$, MSE = .30, $p < .05$, $\eta_p^2 = .29$.

The relationship between TEPRs and memory for various valued words

Next, we computed TEPRs using methodology described by Beatty and Lucero-Wagoner (2000), which operationally

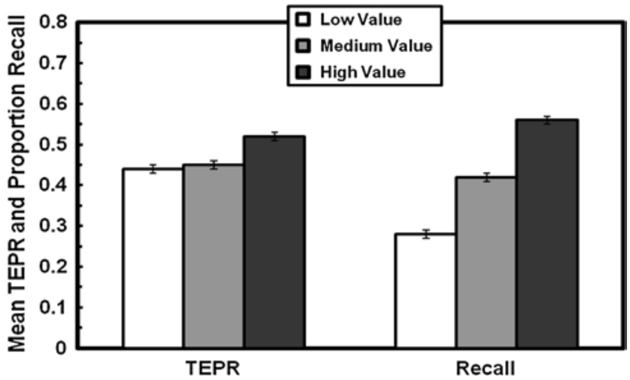

Fig. 2 Mean task-evoked pupillary response (TEPR) in millimeters (*left bars*) and mean proportion recall (*right bars*) for low-value (1–4 point), medium-value (5–8 point), and high-value (8–12 point) words collapsed across lists. *Error bars* represent within-subject standard error of the mean (Loftus and Masson 1994)

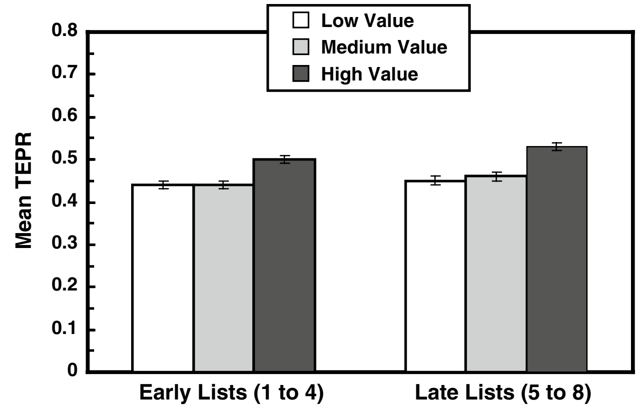

Fig. 3 Mean task-evoked pupillary response (TEPR) in millimeters (*left bars*) for low-value (1–4 point), medium-value (5–8 point), and high-value (8–12 point) words in early lists, where participants displayed low selectivity ($M = .26$, SE = .04) and later lists, where participants displayed higher selectivity ($M = .37$, SE = .04). *Error bars* represent within-subject standard error of the mean (Loftus and Masson 1994)

defined the measure as a change in pupil diameter from a pretrial baseline pupil measurement. To compute TEPRs, the average pupil diameter during the 1,500-ms presentation of the fixation cross that preceded study of a word (pupil baseline) was subtracted from the peak diameter during the 2,000-ms presentation of that word. The mean baseline pupil diameter for low-, medium-, and high-valued words ($M = 7.66$; SE = .01) did not differ as a function of value, $F(11,36) = 1.15$, MSE = .01, $p = .35$, or trial, $F(11,36) = 1.68$, MSE = .13, $p = 12$. Thus, any changes in pupil diameter during the presentation of words cannot be attributed to baseline differences or differences in cognitive load occurring in later trials.

Mean TEPRs and mean proportion correct recall for each value level across lists are presented in Fig. 2. TEPRs and recall both increased with item value. Consistent with these observations, a 1 × 12 (value) repeated-measures ANOVAs revealed effects for value on TEPRs, $F(11,36) = 2.27$, MSE = .09, $p < .05$, $\eta_p^2 = .41$, and within-subject gamma correlations between value and recall ($M = .36$; SE = .04) differed significantly from zero, $t(46) = 8.73$, $p < .001$. Moreover, within-subject gamma correlations between TEPRs and recall of each word were also significant ($M = .07$; SE = .02), $t(46) = 3.72$, $p < .01$. Thus, participants allocated more attention to learning higher- than lower-valued words and increased attention was associated with higher recall.

Changes in TEPRs across lists

As evident in Fig. 1, memory selectivity was higher in later lists than earlier lists. If the differential resource allocation hypothesis can account for these differences in selectivity, then difference in TEPRs should be greater in later than earlier lists (i.e., a value × list interaction is expected). Although the mean SI was significantly higher in late lists ($M = .37$, SE = .04) than in early lists ($M = .26$, SE = .04), $t(46) = 2.83$, $p < .01$, as seen in Fig. 3, the magnitude of TEPRs did not differ between lists, $F(1,46) = .31$, MSE = .02, $p = .60$, $\eta_p^2 = .01$. An effect for value was significant, $F(2,45) = 3.38$, MSE = .12, $p < .05$, $\eta_p^2 = .13$, but the predicted interaction was not, $F(2,45) = .30$, MSE = .01, $p = .74$, $\eta_p^2 = .01$. Thus, there was no evidence that differential resource allocation contributed to improvements in memory selectivity across lists.

Fixation duration for words and their value

Fixation duration (in milliseconds) for words and their value were computed to evaluate the information reduction hypothesis. There were no differences between average fixation times for low-value ($M = 1{,}111.47$), medium-value ($M = 1{,}126.49$), or high-value words ($M = 1{,}123.84$), $F(11,36) = 1.27$, MSE = .03, $p = .28$, or for fixation times on their values (low: $M = 181.21$, medium: $M = 193.57$, high: $M = 204.12$), $F(11,36) = 1.27$, MSE = .03, $p = .28$. We also evaluated whether people reduce how long they fixate on words of lower value after gaining task experience by evaluating differences in fixations on words in early lists and late lists. A 3 (value) × 2 (list: early vs. late) repeated-measures ANOVA revealed that effects for value, $F < 1$, list, $F < 1$, and the interaction were not significant, $F(2,45) = 1.53$, MSE = .01, $p = .23$. Thus, the current data are inconsistent with the information reduction hypothesis.

The relationship between individual differences in selectivity, TEPRs, and fixations

Though the current data indicate that differential resource allocation and information reduction cannot account for the changes in selectivity that occurs with task experience, these hypotheses may be able to account for individual differences in memory selectivity. That is, the most selective learners may allocate cognitive resources differently than less selective learners and highly selective learners may also use strategies like information reduction to selectively encode high-valued words. To evaluate these possibilities, we split participants into quartiles based on their selectivity index and examined TEPRs and fixation times for low-, medium-, and high-valued words. First consider TEPR data which are important for evaluating predictions of the differential resource allocation hypotheses.

The mean TEPR for low-, medium-, and high-valued words for each selectivity quartile is presented in Fig. 4. Inspection of Fig. 4 reveals that TEPRs increased across value for each selectivity quartile and with the exception of the most selective participants (fourth quartile), the magnitude of TEPRs also increased across selectivity quartiles. We computed repeated-measures analyses of covariance (ANCOVA) with selectivity index as a continuous covariate and value (low, medium, and high) as a within-subject factor to evaluate these observations. An effect for value was significant, $F(2,44) = 3.36$, MSE = .03, $p < .05$, $\eta_p^2 = .13$. Effects for selectivity, $F(1,45) = .11$, MSE = .10, $p = .74$, $\eta_p^2 = .002$, and the value × selectivity interaction were not significant, $F(2,44) = 1.42$, MSE = .01, $p = .26$, $\eta_p^2 = .06$. However, given that the data pattern in Fig. 4 suggests that the lack of interaction and effect for selectivity may be due to including the most selective participants in the ANCOVA, we computed a separate ANCOVA model excluding these participants. When participants in the fourth selectivity quartile were excluded from analyses, the ANCOVA model yielded an effect for value, $F(2,32) = 3.25$, MSE = .03, $p < .05$, $\eta_p^2 = .17$, and selectivity, $F(1,33) = 3.67$, MSE = .39, $p = .06$, $\eta_p^2 = .10$, which were qualified by a value × selectivity interaction, $F(2,32) = 3.80$, MSE = .03, $p < .05$, $\eta_p^2 = .19$. Thus, the current data suggest that the differential resource allocation hypothesis can partially account for why some participants are more selective than other participants. However, surprisingly, the most selective individuals did not allocate resources differently than the least selective individuals, which indicate that other processes are also contributing to value-based remembering.

Next, we evaluated the contribution of information reduction to individual differences in selectivity by comparing mean fixation times on low-, medium-, and high-valued words as a function of selectivity quartile. These data are presented in Table 1. Overall, fixation times for low-, medium-, and high-valued words appeared to decrease as memory selectivity increased. However, the most selective participants still fixated on low-valued words, which indicate that they did not reduce information by strategically ignoring low-valued words during study. A repeated-measures ANCOVA model with selectivity index as a covariate and value (low, medium, and high) as a within-subject factor revealed that there was no effect for value on fixation duration, $F(2,44) = 2.54$, MSE = .02, $p = .09$, $\eta_p^2 = .10$. However, an effect for selectivity was significant, $F(1,45) = 5.43$, MSE = 3.43, $p < .05$, $\eta_p^2 = .11$,

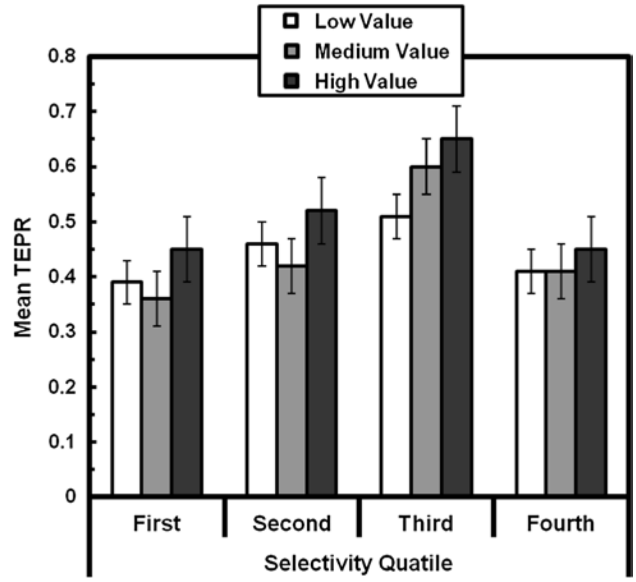

Fig. 4 Mean task-evoked pupillary response (TEPR) in millimeters for low-value (1–4 point), medium-value (5–8 point), and high-value (8–12 point) words as a function of selectivity quartile. The first quartile consists of individuals with the lowest selectivity index and the fourth quartile consists of individuals with the highest selectivity index. *Error bars* represent between-subject (quartile) standard error of the mean

Table 1 Mean fixation duration in milliseconds for words with a low-value (1–4 points), medium-value (5–8 points), and high-value (9–12 points) as a function of selectivity index quartile

Selectivity quartile	Item value		
	Low value	Medium value	High value
First	1,417 (101)	1,395 (108)	1,359 (99)
Second	1,320 (86)	1,345 (85)	1,321 (71)
Third	1,019 (127)	1,053 (125)	1,038 (127)
Fourth	1,040 (141)	1,083 (136)	1,147 (137)

Values are means across individual participant's mean values. Between-subject standard errors of the means are in parentheses. First quartile represents low selectivity individuals and fourth quartile represents high selectivity individuals and this effect was qualified by a value × selectivity interaction, $F(2,44) = 5.03$, MSE = .03, $p < .05$, $\eta_p^2 = .18$. Higher memory selectivity was associated with shorter fixation times for low- ($r = -.37$, $p < .05$), and medium-value words ($r = -.33$, $p < .05$). The least selective individuals fixated longer on high-valued words than the most selective individuals, but this relationship between selectivity and fixation duration was only marginally significant ($r = -.27$, $p = .06$). In summary, these data do not support the information reduction hypothesis.

General discussion

The current experiment used eye tracking methodology to evaluate two non-exclusive hypotheses for how learners selectively encode valuable information. Consistent with the differential resource allocation hypothesis, participants' pupils dilated more when studying high-valued words than when studying low-valued words and recall was also greater for high- than low-valued words. Moreover, participants fixated equally on words regardless of their value, which indicates that participants did not strategically ignore studying low-valued words. Thus, differential resource allocation contributed to value-directed remembering, but information reduction did not.

In the current experiment, differences in attention allocation could not account for changes in selectivity with task experience. One explanation for why TEPRs remained consistent across lists, but selectivity increased, is that TEPRs may be tapping an automatic allocation of attention to encode valuable information and the increases in selectivity may be in part due to more strategic processes (e.g., use of mnemonic strategies during encoding). Recent research suggests that people can allocate attention rapidly and without awareness to complete a highly rewarding task (Bijleveld et al. 2012a). For instance, when people are primed subliminally with a high reward (a coin presented for 17 ms) prior to performing a complex finger-tapping task, they respond faster than if they were primed with a low reward (Bijleveld et al. 2012b). People's pupils also dilate more when primed subliminally with a high reward versus a low reward under a high memory load in a digit span task (Bijleveld et al. 2009). Thus, people's attention allocation in response to item reward may not always be strategic in nature.

Though differences in TEPRs were not associated with changes in selectivity across lists, they were associated with individual differences in selectivity. People who displayed moderate memory selectivity (2nd and 3rd quartile in Fig. 4) allocated more attention to high-value words than people who displayed low memory selectivity (1st quartile). However, the most selective individuals (4th quartile) allocated resources more sparingly than less selective individuals. They also fixated less on words regardless of their value (Table 1). Though speculative, these results suggest that highly selective individuals may process important information more efficiently than individuals with lower memory selectivity. They essentially allocate fewer resources to achieve higher gains in performance.

Research examining pupillometry for individuals who vary in general intelligence and working memory span have revealed findings consistent with the speculation above (Ahern and Beatty 1979; Heitz et al. 2008). For example, people who score high on the Scholastic Aptitude Test (SAT) allocate less attention to performing difficult math, comprehension, and digit span tasks than people who score low on the SAT (Ahern and Beatty 1979). People with higher working memory spans also allocate less attention when recalling digits in an operation span tasks than people with low working memory spans (Heitz et al. 2008). Given that previous research has linked recall of high-valued words to working memory span and attentional control (Castel, Balota, and McCabe 2009), it is possible that highly selective individuals in the current experiment were also higher in these executive function abilities than people with lower memory selectivity. If so, the pattern of TEPRs in Fig. 4 and fixations in Table 1 would be expected and it could reflect efficient deployment of attention to encoding valuable information. However, given the exploratory nature of the individual difference analyses we conducted, further investigation is necessary to verify these conclusions.

One alternative explanation for the pupil effects observed in the current experiment is that they reflect emotional arousal that occurs when participants view an item's value and not increased attention to high- relative to low-valued words. Though incentives may be emotionally arousing, incentives alone do not influence pupil dilations (Bijleveld et al. 2009; Chiew and Braver 2013; Ewing and Fairclough 2010; Kahneman and Peavler 1969). Instead incentives are motivating and lead to the mobilizations of cognitive resources to perform a highly rewarding task. Consider findings from Kahneman and Peavler (1969) in which participants studied nouns paired with digits that signaled whether participants would receive a low reward for remembering that word (1 cent) or a high reward (5 cents). On each trial, a digit was presented aurally for 3 s and was followed by a 3-s presentation of a noun. Average pupil diameter did not differ during the presentation of digits. However, participants' pupils dilated more during the presentation of words worth a high reward than words worth a low reward. These results among others (Bijleveld et al. 2009; Chiew and Braver 2013; Ewing and Fairclough 2010; Kahneman and Peavler 1969) suggest that differences in TEPRs in the current experiment reflect differential resource allocation during encoding and not differences in emotional arousal in response to an item's value. Future research could further examine this issue by presenting the word followed by the value (see also Castel et al. 2002, Experiment 2), to disentangle the contribution of item processing and arousal associated with value.

In the current experiment, we failed to find support for the information reduction hypothesis. However, our methodology may have discouraged use of an information reduction strategy. People were placed in a chin rest which oriented their gaze toward the center of the computer screen where words and point values were located. Directing participants gaze toward the center of the computer screen may have inadvertently encouraged them to always read the words on each trial. However, participants did view a fixation cross before each trial and words and point values appeared in a different location than this fixation cross (i.e., words to the left and value to the right of this location). Thus, people did have to move their eyes to read words. Most important, the mean fixation duration for words on each trial was longer than would be expected if people were just reading them. Our preferred interpretation of these results is that people attempted to encode words on each trial which would be inconsistent with the information reduction hypothesis.

Effectively encoding valuable information may require strategic processing that goes beyond differential resource allocation during encoding or information reduction. This strategic processing may involve evaluating task conditions and developing an agenda that specifies how to encode what information the learner values (Ariel et al. 2009; Dunlosky and Ariel 2011). Consider the changes in memory selectivity between early lists and late lists depicted in Fig. 1. One explanation for these changes is that learners used feedback about poor value-based performance in early lists to change their encoding strategies in later lists (see also McGillivray and Castel 2011). This type of metacognitive monitoring and control involves applying knowledge about strategy effectiveness to maximize the likelihood that important information is remembered and it may involve shifting from shallow to deeper encoding strategies across lists. Regardless, further research is needed to better understand the role of strategic processing in encoding valuable information.

In summary, efficient memory performance requires learners to selectively encode and later retrieve important goal-relevant information. To do so, learners may strategically conserve or restrict attentional resources when presented with low-valued information, but then increase this allocation when valuable information is encountered. This differential resource allocation improves value-directed remembering, but other more strategic encoding and retrieval processing may play an additional role in memory selectivity.

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