

Variation in Attention at Encoding: Insights From Pupillometry and Eye Gaze Fixations

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In 2 experiments, eye-tracking was used to examine individual differences in attention during encoding and their relation to associative learning. Pupillary responses were used as an indicator of the amount of attention devoted to items, whereas eye fixations provided a means of assessing attentional focus among items within each to-be-remembered word pair. In both experiments, participants performed a paired associates (PA) cued recall task while pupil diameter and eye fixations were simultaneously recorded. Results from Experiment 1 revealed that larger pupillary responses at encoding, as well as more alternating fixations between the Cue and Target items for each word pair (i.e., switches), was associated with increased learning ability. Critically, while Experiment 2 revealed that effective strategy use partially accounted for the relationship between pupillary responses and PA recall accuracy, pupillary responses still explained unique variance in PA recall accuracy—a result that held even when controlling for the influence of working memory capacity and long-term memory ability. Collectively, the results suggest attentional abilities at encoding are vital for successful learning.

Keywords: attention, eye-tracking, individual differences, learning, strategy use

The ability to learn and remember relevant information is essential for a variety of tasks and situations we encounter in our day-to-day lives. Whether it is remembering one's anniversary or remembering the order of operations for an upcoming algebra exam, it is critical that one pays attention to information at learning to ensure it is properly encoded. Indeed, it is well documented that information we pay more attention to tends to be remembered better than information that we pay less attention to. For instance, prior work has shown that dividing attention at learning impairs ensuing memory performance (Anderson, Craik, & Naveh-Benjamin, 1998; Baddeley, Lewis, Eldridge, & Thomson, 1984). Other research (Craik & Lockhart, 1972) has demonstrated that items that receive shallow processing at encoding are similarly associated with impaired recall performance relative to items that receive more elaborative processing. Despite the aforementioned effects, little research has examined whether variation in attentional abilities at encoding are important for individual differences in learning. The present study, therefore, sought to examine two mechanisms by which attention could influence learning ability. Specifically, we examined how individual differences in (a) the amount of resources allocated to learning (i.e., intensity of atten-

tion) and (b) what information individuals attend to (i.e., attentional focus) relate to each other and to overall learning ability.


Background

One critical factor in determining how well something is learned is how much attention is devoted to encoding processes during the learning episode. Theoretically, more elaborative and deep processing of stimuli should require more attentional resources than shallower processes (e.g., rehearsal; Craik & Byrd, 1982). As such, when more attention is devoted to learning, the to-be-learned information should be encoded with stronger memory representations and, consequently, should have a higher likelihood of being recalled when a search through long-term memory is undertaken. The amount of attentional resources that are devoted to learning reflect the overall intensity of attention being directed to the to-be-learned material. As previously mentioned, evidence for this notion has primarily relied on dual-task paradigms where participants are given materials to learn (such as a list of words) while also performing some distractor task (such as a digit detection task). The typical result is that memory performance is reduced under conditions of divided attention compared with conditions of full attention (e.g., Baddeley et al., 1984; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Murdock, 1965). When attention is not fully devoted to encoding, items are weakly encoded, and chances of recovery are low. Collectively, this prior work suggests that the process of learning new information is an attentionally demanding one.

A potential indicator of the intensity of attention is task-evoked pupillary responses (TEPRs)—changes in pupil dilation relative to baseline levels in response to cognitive demands (Beatty & Lucero-Wagoner, 2000; Goldinger & Papesch, 2012; Hess & Polt, 1964; Kahneman & Beatty, 1966; Laeng, Sirois, & Gredebäck,

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2012). Larger TEPRs have been associated with increased attention allocation across a number of tasks. For instance, TEPRs have been shown to increase as a function of memory load in traditional short-term memory (STM) tasks (Kahneman & Beatty, 1966; Peavler, 1974), as well as a function of the difficulty of math problems (Hess & Polt, 1964). Results such as these led Kahneman (1973) to suggest that pupil dilation is a reliable and valid psychophysiological marker of attentional allocation. That is, TEPRs correspond to the intensive aspect of attention and are an online indicator of the amount of attentional effort devoted to a given item (i.e., the “intensity of attention”; Kahneman, 1973; see also Just & Carpenter, 1993)

Of particular relevance to the current study, research has demonstrated that TEPRs at encoding are also associated with long-term memory performance (Ariel & Castel, 2014; Engle, 1975; Goldinger & Papesh, 2012; Kafkas & Montaldi, 2011; Naber, Frässle, Rutishauser, & Einhäuser, 2013). For example, Otero, Weekes, and Hutton (2011) manipulated shallow versus deep encoding conditions in a traditional remember/know paradigm. Correct responses at recall were higher for items in the deep encoding condition, and these items were associated with increased pupil dilation relative to words in the shallow encoding condition. Thus, when compared with shallow processing, deep processing reflected more effortful attention allocation. Similarly, Papesh, Goldinger, and Hout (2012) administered a recognition task and showed that items recognized with the greatest confidence were associated with larger TEPRs at encoding. Other research has extended these findings to value-directed remembering (Ariel & Castel, 2014; Miller, Gross, & Unsworth, 2019), such that words high in value were associated with larger TEPRs, as well as improved recall. Although these studies suggest larger TEPRs at encoding are associated with better memory, it is important to acknowledge that the relationship between pupil size and the quality of encoding appears to be paradigm specific. Namely, using incidental learning conditions, Kafkas and Montaldi (2011) demonstrated the opposite pattern when predicting recognition memory: Subsequently remembered items were associated with smaller TEPRs during encoding. Nonetheless, prior work adopting similar, intentional learning conditions (i.e., Ariel & Castel, 2014; Goldinger, He, & Papesh, 2009; Papesh et al., 2012) suggests items that receive the most attention at encoding are typically associated with larger TEPRs and better recall performance (though, see Naber et al., 2013).

One issue with the research reviewed thus far is that it has largely neglected examining variation between individuals. There are large and important individual differences in recall abilities. A number of studies have demonstrated that recall measures are related to other long-term memory measures (e.g., item recognition, source memory, cued recall) and other cognitive abilities, such as intelligence and working memory (e.g., Beier & Ackerman, 2004; Carroll, 1993; Unsworth, 2019; Unsworth, Brewer, & Spillers, 2009). Although prior work has suggested a number of important reasons for these individual differences—search efficiency, strategic encoding processes, monitoring abilities (see Unsworth, 2019 for review)—other research suggests variation in attention allocation at encoding is likely another reason for individual differences in recall abilities (Craig & Byrd, 1982; Kane & Engle, 2000; Miller et al., 2019; Unsworth, 2019).

In particular, we (Miller et al., 2019) recently suggested that individual differences in the intensity of attention are related to memory performance. The intensity of attention was indexed via TEPRs during the encoding phase of a delayed free-recall task. Across two experiments, we found that TEPRs at encoding were positively related to memory performance ($r_s = .18$ and $.22$), indicating that individuals who allocate more attention to items during encoding tend to remember more words. Not only were pupillary responses at encoding related to overall delayed free recall accuracy, but TEPRs were also positively related to individual differences in working memory capacity (WMC) and long term memory (LTM) abilities independent of delayed free recall. Further analyses revealed, however, that TEPRs at encoding no longer predicted unique variance in memory performance when taking LTM ability and WMC into account.

Although these results suggest that variation between the intensity of attention at encoding and memory performance is explained by WMC and LTM ability, delayed free recall paradigms may not be the best way to assess variation in the intensity of attention per se. That is, Miller and colleagues (2019; see also Unsworth & Miller, 2019) suggest TEPRs in free recall paradigms are confounded with cognitive load. So, in these cases, TEPRs reflect (a) attention allocation across items in a list (list-level changes) and (b) attention allocation within each item regardless of serial position (item-level changes). If one is interested in examining how variation in attention allocation within each item relates to recall and learning ability, a task that allows us to assess TEPRs on an item-by-item basis (without the confound of list effects) would be preferable. For this reason, the present study monitored pupillary responses during the encoding phase of a paired-associates (PA) cued recall task. Using this paradigm, we should be able to better observe whether variation in the intensity of attention is a source of individual differences in learning abilities.

Of course, attention is not only needed to allocate sufficient processing resources to relevant information but also to select relevant information for ongoing processing (Chun & Turk-Browne, 2007). The behavior of selecting items to study fundamentally determines which information will be available for memory at test, and a means of monitoring this process is via eye fixations. For instance, van der Linde and colleagues (2009) showed that regions within natural scenes that attracted more fixations were better remembered at test than regions that attracted less fixations (see also Pertzov, Avidan, & Zohary, 2009). Similarly, Kafkas and Montaldi (2011) demonstrated that increased fixations at encoding were associated with increased recognition memory strength for single everyday objects. Another study (Henderson, Williams, & Falk, 2005) discovered that increased fixations at encoding were also associated with improved memory for faces. More recent work has also shown that increased eye fixations at encoding are associated with increased neural activity in the hippocampus (Liu, Shen, Olsen, & Ryan, 2017). Considering the hippocampus plays an important role in episodic memory (e.g., Tulving & Markowitsch, 1998), results such as these led Voss, Bridge, Cohen, and Walker (2017) to suggest exploratory viewing is essential to memory formation processes supported by the hippocampus. More specifically, the hippocampus is thought to produce brief memory signals necessary to guide visual exploration in such a way that all relevant information is attended to, resulting in a more cohesive episodic memory. Therefore, an

important link exists between eye-gaze fixations and memory performance, insofar that fixations may play a functional role guiding one's attentional focus.

Other work has expanded on the role of fixations in memory by examining transitions in fixations (i.e., switches) at learning. In the case of associative learning, a switch is defined as a fixation on either the Cue or Target when the previously fixated object was the opposite. Using a standard associative recognition paradigm, [Kamp and Zimmer \(2015\)](#) presented young and old adults with pairs of colored pictures depicting everyday objects. An analysis of switches over time revealed that, among young adults, increased switches within the first second of encoding were associated with increased item recognition at recall. [Kamp and Zimmer \(2015\)](#) suggested transitions such as these are indicative of alternating attentional focus, whereby a relational link (i.e., *mediator*) is generated. So, young adults were seemingly quick to create an associative link, which was further elaborated upon in working memory (indexed via EEG frontal slow waves).

It is apparent that viewing behavior—particularly fixations and alterations in fixations—impacts memory performance. Despite this knowledge, little memory research has taken eye fixations into account ([Voss et al., 2017](#)), and no work has examined how variation in viewing behavior may relate to learning ability. The current study sought to explore this question by monitoring fixations during learning of a PA cued recall task. In doing so, we hoped to better understand whether individual differences in attentional focus at learning predicts recall performance. Furthermore, whereas previous research has explored viewing behavior in the context of complex scenes or everyday objects, the current study focused on the role of fixations in verbal associative memory formation.

Overall, eye tracking appears to be a promising means of assessing how various attentional abilities vary at learning. TEPRs can be used to measure the amount of attentional resources directed to the to-be-learned material (i.e., intensity of attention), whereas fixations provide a means of monitoring one's attentional focus and, as a result, the content available in memory. Moreover, switches may reflect alternations in attentional focus, which may serve a crucial role in binding relational features between items into a durable memory representation. However, as previously mentioned, it remains unclear how variation in these processes may relate to learning ability. This question was tested in two experiments. In each experiment, participants completed a verbal PA cued recall task while pupil diameter and eye fixations were simultaneously recorded.

Experiment 1

Experiment 1 had three primary aims. First, we sought to examine whether individual differences in the intensity of attention impact learning ability. We tested this notion by using pupil dilation as an online indicator of the intensity of attention devoted to items during learning. Individuals who can increase (and sustain) attention to items during learning should encode those items better than individuals who cannot increase the allocation of attention at encoding, leading to differences in subsequent performance ([Miller et al., 2019](#)). A second, more exploratory aim was to examine whether individual differences in attentional focus also relate to learning ability. Do individuals who selectively view the

Target and Cue display better recall accuracy? One may speculate that a reason why low learning individuals perform worse is because these individuals may only focus on one of the relevant stimuli (e.g., the Cue) as opposed to both the Target and Cue. In a related vein, is learning ability related to how viewing behavior changes across the encoding period? To address these questions, eye-gaze fixations were used to monitor which information individuals attend to during verbal PA learning.

We also examined alternations in eye-gaze fixations (i.e., switches) in an effort to extend [Kamp and Zimmer's \(2015\)](#) findings to verbal PA learning. Prior research (see [Richardson, 1998](#) for review) has demonstrated that memory performance is best for word pairs when individuals report using mediational strategies to form associative links between the words (as opposed to when they use a more rehearsal-based strategy). The ability to generate and remember mediators used during learning has even been shown to account for age-related deficits in associative learning ([Dunlosky, Hertzog, & Powell-Moman, 2005](#)). So, if switches between Cue and Target items are indicative of one's ability to generate relational links between items within a word pair, it seems plausible that individuals who display more switches at learning may similarly display better memory performance.

Finally, given that prior work ([Beier & Ackerman, 2004](#); [Carroll, 1993](#); [Unsworth et al., 2009](#)) has demonstrated that WMC and LTM ability are important for learning, we sought to examine whether individual differences in attention at encoding still relate to learning ability when taking these factors into account. Consequently, if the intensity of attention and attentional focus predict learning ability, a critical point of analysis was to determine whether individual differences in WMC and LTM account for these relationships. To address this notion, participants completed a battery of WMC tasks and LTM tasks before completing a verbal PA cued recall task made up of three word-pair lists, each containing 10 word-pairs. Pupil diameter and eye fixations were simultaneously recorded throughout the duration of this task.

Method

Participants and procedure. A total of 134 participants (68% female) were recruited from the human subject pool at the University of Oregon. All participants were between the ages of 18 and 31 ($M = 19.45$, $SD = 2.00$). Nine participants were excluded from all analyses because of excessive missing pupil data on the paired associates cued recall task. Three more participants were excluded because they were either not proficient in English or scatterplots revealed them to be outliers (final $N = 122$). All participants were awarded course research credit for participation. After obtaining informed consent and demographic information, all participants completed three complex span tasks: the operation span task (Ospan), the symmetry span task (Symspan), and the reading span task (Rspan). Following the WMC tasks, participants were then moved to a dimly lit room where they first completed a delayed free-recall task followed by a PA cued recall task. Pupil diameter was simultaneously recorded binocularly at 120 Hz using a Tobii T120 eye-tracker during both of these tasks. Prior to beginning the PA task, participants were seated 60 cm from the monitor, and a 9-point standard calibration procedure began. To calibrate the eye tracker, participants were asked to fixate on a series of 9 gray dots presented on a white background. The Tobii

Eye Tracker measures aspects of the participant's eyes and uses them together with an internal, anatomical 3D eye model to calculate the mapping between the identified gaze position on the display and the eye tracker's estimate of that position. Recalibration occurred whenever the criterion defined by the proprietary software was not met. All participants were successfully calibrated within the first few attempts. In addition, a headrest, mounted at the front of the table holding the eye-tracker, was used to reduce any potential influence of uncontrolled head movements. Upon completion of the PA task, participants were moved back into an individual run room where they completed a picture source recognition task. We should also note that participants completed the tasks reported herein as part of a larger experimental test battery lasting approximately 1.5 hr. Because the other tasks administered during the experimental session do not relate to the current study, they are not reported. The procedure was approved by the Institutional Review Board of the University of Oregon. All participants were treated according to the ethical standards of the American Psychological Association and were debriefed following the session.

WMC tasks.

Ospan. Participants solved a series of elementary math problems while remembering unrelated letters. First, on computer participants were presented with a math operation (e.g., $(4 \times 1) + 2 = ?$) in which they had to click the mouse to indicate that they had solved the problem. A new screen then appeared with an answer to the math solution (e.g., 6), whereby participants had to indicate whether the answer listed onscreen was correct or incorrect via mouse click (e.g., in the case above, the answer 6 would be correct). Upon completion of the math operation, participants were then presented with a letter (e.g., F, H, J, K, L, N, P, Q, R, S, T, and Y) for 1 s. Immediately after letter presentation, the next math problem was presented. Set sizes varied randomly from three to seven math operation/letter strings, and participants had to complete 2 trials of each set size for a total possible score of 50. At recall for each set, letters from the corresponding set had to be recalled in order by selecting the relevant letters. See [Unsworth, Heitz, Schrock, and Engle \(2005\)](#) for more details.

Symspan. Participants solved symmetry judgments while remembering the location of a sequence of red squares within a matrix. Symmetry judgments consisted of an 8×8 matrix of squares in which some of the squares were filled black and the remaining squares remained white. Participants indicated whether the pattern created by the filled squares was symmetrical about the vertical axis. Once participants indicated whether they believed the pattern was symmetrical or nonsymmetrical, participants were shown a 4×4 matrix with one of the cells filled red for 650 ms. Immediately after the presentation of the red square matrix, the next symmetry judgment trial began. Set sizes randomly ranged from two to five, and there were two trials of each set size for a total possible score of 28. Participants were asked to recall the sequence of red-square locations based on the order in which they were presented across the corresponding trial. Participants indicated the appropriate location of each red-square by clicking on cells in an empty matrix. See [Unsworth, Redick, Heitz, Broadway, and Engle \(2009\)](#) for more details.

Rspan. While remembering the same unrelated letters as in the Ospan, participants provided judgments about a series of sentences. More specifically, participants read a sentence containing

10 to 15 words and determined whether or not the sentence made sense to them (e.g., "Every now and then I catch myself swimming blankly at the wall"). Nonsense sentences were created by modifying a single word from an otherwise ordinary sentence (e.g., changing *staring* to *swimming* in the case above). Upon indicating whether the sentence made sense or not, participants were then presented with a letter for 1 s. Set sizes randomly varied from three to seven sentence/letter strings, and participants had to complete two trials of each set size for a total possible score of 50. At recall for each set, letters from the corresponding set had to be recalled in order by selecting the appropriate letters. See [Unsworth, Redick, et al. \(2009\)](#) for more details.

Factor WMC score. All analyses involving WMC used a WMC factor score created for each participant by entering scores on the three complex span working memory measures into a factor analysis using principal axis factoring. Factor loadings were as follows: Ospan (0.96), Symspan (0.39), and Rspan (0.66). This variable allowed us to treat WMC as a continuous variable in all analyses.

LTM tasks.

Delayed free recall. Participants were administered a delayed free-recall task consisting of 10-word lists containing 10 words each. Word lists were initially composed of randomized nouns selected from the Toronto word pool ([Friendly, Franklin, Hoffman, & Rubin, 1982](#)). All participants received the same lists of words and were instructed to recall as many words as possible from each list. Words were presented onscreen for 3 s each. Following presentation of the last word within each list, a 16-s distractor task began that required participants to verbally report a series of 8 three-digit numbers in descending order (adapted from [Rohrer & Wixted, 1994](#)). Each three-digit string was presented onscreen for 2 s. After the distractor task, three question marks appeared in the center of the screen to prompt participants to recall as many words as possible within a 45-s window. Participants typed their responses in any order they wished and pressed *enter* after each word, thereby clearing the screen. It is important to further note that this task manipulated encoding conditions via value-directed remembering, and pupil diameter was also recorded during the task. These data, along with more task specifics, are reported in [Miller et al. \(2019, see Experiment 2\)](#). For the purpose of this paper, we only use mean recall data for the DFR task to create our LTM factor composite.

Picture source recognition. During the encoding phase, participants were presented with a picture (30 total pictures) in one of four different quadrants onscreen for 1 s. Participants were explicitly instructed to pay attention to both the picture (item) as well as the quadrant it was located in (source). At test, participants were presented with 30 old and 30 new pictures in the center of the screen. Participants were required to indicate if the picture was new or if it was old. If the picture was deemed old, they also had to specify what quadrant the picture was presented in via key press. Thus, on each test trial participants pressed one of five keys indicating new, old-top left, old-top right, old-bottom left, or old-bottom right. Participants had 5 s to press the appropriate key to enter their response. A participant's score was the proportion of correct responses.

Factor LTM score. Scores on the LTM tasks (delayed free recall and picture source recognition) were similarly entered into a factor analysis using principal axis factoring to create a LTM

factor score for each participant. The factor loadings were as follows: delayed free recall (0.59) and picture source recognition (0.59).

Paired associates cued-recall task. After calibration of the eye-tracker, participants were administered 3 lists of 10 word-pairs each. Similar to the delayed free-recall task, word-pair lists were composed of randomized common nouns selected from the Toronto word pool (Friendly et al., 1982), and all words were between three and five letters in length. Note that words were not allowed to repeat across tasks. Words (as well as the mask preceding/following each word) were presented in black text in Arial font (font size = 24) on a light gray background. Properties such as ambient light, screen brightness, contrast, and so forth were held constant across all participants. The task began with a “Ready?” signal onscreen, at which point participants pressed the spacebar to begin. Each list began with the same “Ready?” signal. Each word pair was preceded and followed by a mask of five plus signs replacing each word that had previously been listed onscreen for 2 s (see Figure 1). This Fixation period was used to baseline correct pupillary responses on a trial by trial basis (i.e., each word pair had its own baseline). Each word pair was presented horizontally for 3 s. All word pairs were associatively and semantically unrelated. Participants were told that the cue would always be the word on left and the target would be on the right. After the presentation of the last word pair, participants saw the cue word and ??? in place of the target word. Participants were instructed to type in the target word from the current list that matched cue. Cues were randomly mixed so that the corresponding target words were not recalled in the same order as they were presented. Participants had 5 s to type in the corresponding word. A participant’s score was the proportion of items recalled correctly.

Results

All measures displayed adequate variability and were approximately normally distributed (i.e., skewness < 2; kurtosis < 4; Kline, 2016; see Table 1). To observe whether variation in attentional abilities are important for learning, PA accuracy was added as a covariate in a series of repeated-measures ANCOVAs. For graphical purposes only, using a quartile split, the uppermost 25% of performers on the PA task was categorized as high learning ability, whereas the lowermost 25% performers were categorized as low learning ability.

Eye-tracking.

Task-evoked pupillary responses (TEPRs). As previously mentioned, pupil diameter was assessed continuously throughout

Table 1
Descriptive Statistics and Reliability Estimates for All Measures

Measure	M	SD	Skew	Kurtosis	Reliability
Ospan	37.77	8.18	-0.80	0.60	.67
Rspan	38.27	7.07	-0.54	0.32	.64
Symspan	19.56	5.04	-0.79	0.50	.61
DFR	0.53	0.16	0.38	0.19	.92
PA	0.41	0.26	0.35	-0.84	.85
PicSource	0.71	0.18	-1.38	2.08	.93
TEPR	0.04	0.08	0.63	0.76	.96
CueFixProp	0.41	0.09	-0.26	0.20	.85
TargetFixProp	0.45	0.08	-0.42	0.83	.82
Switches	2.58	0.75	0.90	2.80	.82

Note. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; DFR = delayed free recall; PA = paired associates cued recall; PicSource = picture source recognition; TEPR = task-evoked pupillary response during the last encoding bin (the final 200 ms); Cue-FixProp = proportions of fixations on cue; TargetFixProp = proportion of fixations on target.

the PA task. Data from each participant’s left eye were used for analyses, and missing data points associated with eye tracker malfunction, blinks, or off-screen fixations were excluded from averaging (i.e., we did not interpolate missing pupil data). TEPRs were baseline corrected on a pair by pair basis by subtracting mean baseline diameter prior to word onset from the average pupil diameter during the 3-s encoding phase for each word. In addition, the pupil data for the 3-s encoding phase was broken down into a series of 200-ms timeframes, resulting in 15 total baseline corrected bins. However, a further inspection of the data revealed that TEPRs during the first 1,200 ms were strongly confounded by fixations. As will be demonstrated shortly, the vast majority of fixations occurred during this period. These fixations, in turn, resulted in large changes in luminance (see Figure 2A), meaning TEPRs during the first 1,200 ms largely reflected changes in the pupillary light reflex (e.g., Binda, Pereverzeva, & Murray, 2013), not the intensity of attention. To better illustrate pupil dynamics related to the intensity of attention, the bin representing the end of the pupillary light reflex was used for baseline correction (see Wang, Brien, & Munoz, 2015 for similar method). In other words, we corrected TEPRs by using 1,200 ms as our reference point, leaving a total of nine bins for our TEPR-related analyses. We subtracted mean dilation at 1,200 ms from each ensuing bin.

To examine changes in pupil dilation during encoding, mean TEPRs were submitted to a repeated-measures ANOVA with Bin as a within-subjects factor (nine levels). Results revealed a significant main effect of Bin, $F(8, 968) = 6.80, p < .001$, partial $\eta^2 = .05, MSE = .001$. Figure 2B shows that, indeed, pupil diameter increased throughout the encoding period for each word ($M = .03, SE = .00$). Next, PA accuracy was added as a covariate to observe whether variation in the intensity of attention (indexed via TEPRs) relates to learning ability. The repeated-measures ANCOVA revealed a main effect of PA accuracy, $F(1, 120) = 20.63, p < .001$, partial $\eta^2 = .15, MSE = .026$, suggesting individuals who best learned the task had larger TEPRs on average than those who did not learn the task as well, $r = .38, p < .001$. Critically, the interaction between PA accuracy and bin was also significant, $F(8, 960) = 6.20, p < .001$, partial $\eta^2 = .05, MSE = .001$. Figure 3A shows that TEPRs increased throughout the encoding period for

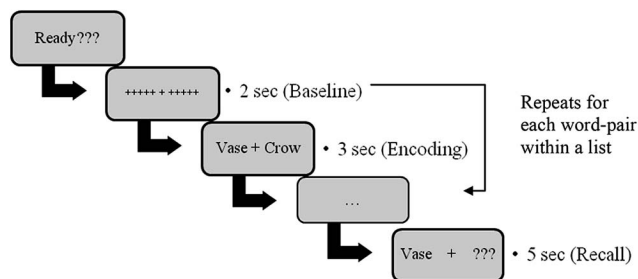


Figure 1. Schematic of the experimental task.

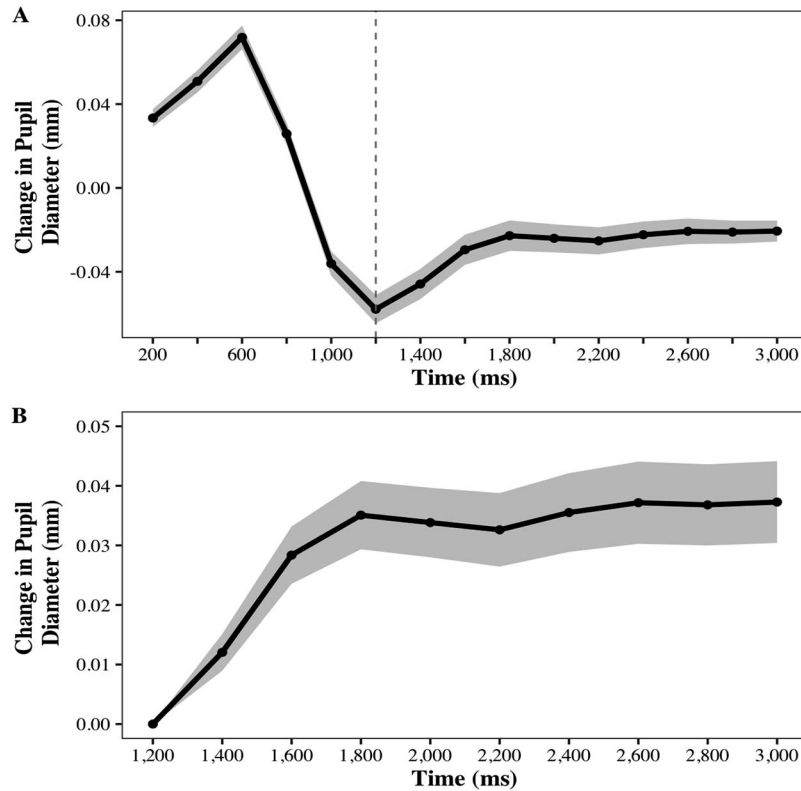


Figure 2. (A) Change in pupil diameter (mm) across the 3-s encoding period for each word-pair. (B) Change in pupil diameter during encoding using 1,200 ms as our starting point and subtracting mean dilation at 1,200 ms from each of the following bins. Shaded areas reflect 1 SEM.

high learning ability individuals but not for low learning ability individuals, whereas Figure 3B demonstrates an increase in the correlation between PA accuracy and TEPRs across the encoding period. It therefore seems apparent that individual differences in the intensity of attention are related to learning ability.¹

Fixations. Next, we examined fixations as a function of Location (Cue, Target, Fixation, or Other) to better understand what information individuals attend to during verbal associative learning and whether this, in turn, relates to recall performance. Four regions of interest (ROIs), corresponding to the four previously mentioned locations, were defined. The location *Fixation* simply represents the central fixation cross between the Target and Cue, whereas *Other* refers to all other locations on the monitor. Proportions of fixations were determined by first summing the number of times an individual fixated on a given object during the 3-s encoding phase. Samples were collected every 16 ms. This number was then divided by an individual's total number of fixations.

Proportions of fixations were submitted to a 4 (Location; within-subjects factor) \times 15 (200-ms Bin; within-subjects factor) repeated-measures ANOVA. Results revealed a main effect of Location, $F(3, 363) = 646.42, p < .001$, partial $\eta^2 = .84, MSE = .13$, suggesting that people fixated most on the Target ($M = .46, SE = .01$), followed by the Cue ($M = .41, SE = .01$), Fixation ($M = .10, SE = .01$), and Other ($M = .04, SE = .01$). There was also a significant interaction between Location and Bin, $F(42,$

$5082) = 125.91, p < .001$, partial $\eta^2 = .51, MSE = .01$. Figure 4 demonstrates that, initially, participants fixated most on the Cue. Approximately 600 ms into the encoding period, however, time spent fixating on the Target began to predominate viewing behavior (peaking around 800 ms). Finally, about 1,800 ms into the encoding period, participants demonstrated little to no differences in fixations between Targets and Cues. Figure 4 further reveals that participants spent little time viewing Central Fixation. Though, there appeared to be an upward trajectory in time spent viewing Fixation during the final 2 s of the encoding period (linear trend: $F[1, 121] = 73.24, p < .001, \eta^2 = .38, MSE = .03$). The line representing *Other* suggests participants rarely fixated on anything other than the Cue, Target, or Central fixation.

PA accuracy was then added as a covariate to observe whether variation in viewing behavior (i.e., what info individuals selectively focus their attention on during study) relates to learning

¹ We examined subsequent memory effects to see whether pupillary responses during encoding would predict subsequent recall within individuals. To maintain consistency with our individual differences analyses, we averaged TEPRs for the final encoding bin (the final 200 ms) separately for recalled and forgotten items. Experiment 1 results revealed no significant TEPR differences between subsequently remembered ($M = .023, SE = .013$) and subsequently forgotten items ($M = .037, SE = .008$), $t(117) = -1.002, p = .318$. Experiment 2 results similarly revealed no significant differences between remembered ($M = .024, SE = .014$) and forgotten items ($M = .041, SE = .009$), $t(125) = -1.125, p = .263$.

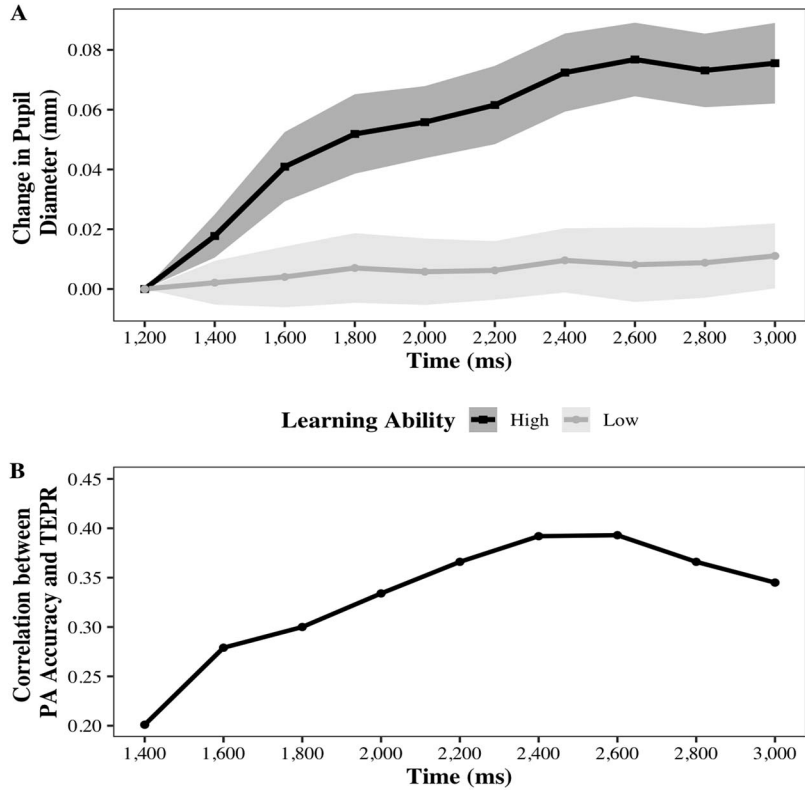


Figure 3. (A) Change in pupil diameter (mm) across the encoding period for each word-pair as a function of high ($n = 32$) versus low ($n = 30$) learning ability. Shaded areas reflect 1 SEM. (B) Change in correlation between paired associates (PA) accuracy and task-evoked pupillary response (TEPR) across the encoding period for each word-pair.

ability. The 4 (Location; within-subjects factor) \times 15 (200-ms Bin; within-subjects factor) repeated-measures ANCOVA revealed a significant three-way interaction between Location, Bin, and PA accuracy, $F(42, 5040) = 3.44, p < .001, \text{partial } \eta^2 = .03, \text{MSE} = .01$. Figure 5 demonstrates that learning related differences in

fixations appear to be driven by low ability individuals' tendency to display a delay in when they view the Target most. That is, both high and low learning ability individuals first briefly fixate on the Cue then transition to fixate on the Target (followed by little to no differences in fixations between Targets and Cues around 1,800 ms

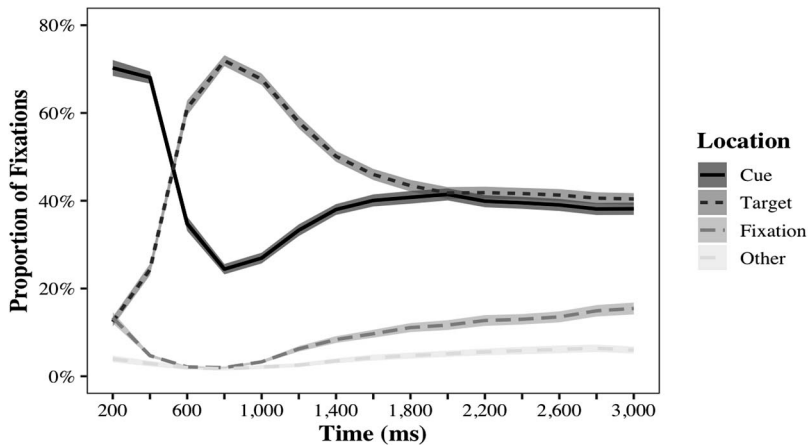


Figure 4. Proportion of fixations across the 3-s encoding period as a function of Location (Cue, Target, Fixation, and Other). Shaded areas reflect 1 SEM.

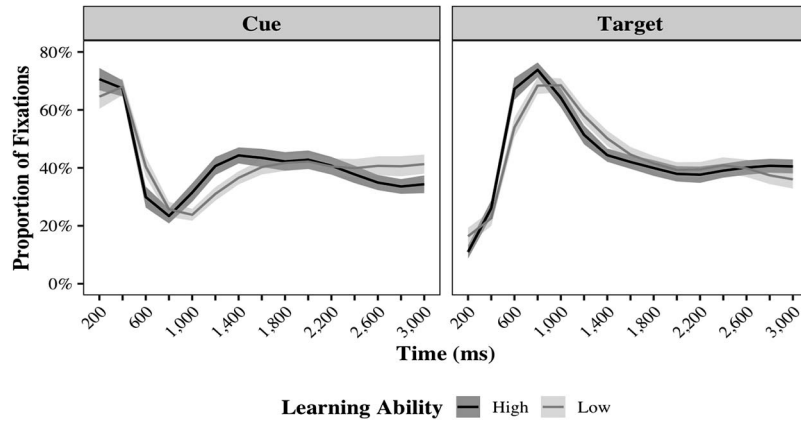


Figure 5. Proportion of fixations across the 3-s encoding period as a function of Location (Cue vs. Target) and Learning Ability (High vs. Low). Shaded areas reflect 1 SEM.

into the encoding period). The difference, then, is that low learning ability individuals do not transition to viewing the Target until slightly later than do high learning ability individuals. Moreover, during the final 2 s of the encoding period, low learning ability individuals do not appear to transition back to viewing the Cue in equal proportion to the Target until approximately 400–600 ms after their high ability counterparts.

Switches. For each second of the encoding period, we summed Cue-to-Target and Target-to-Cue switches. A switch was defined as a fixation on either the Cue or Target ROI when the previously fixated ROI was the opposite. Means were obtained by averaging across Cue-to-Target and Target-to-Cue switches. Consistent with prior work (Kamp & Zimmer, 2015), a repeated-measures ANOVA with Bin (1 s; three levels) as a within-subjects factor revealed a significant effect of Bin, $F(2, 242) = 219.20, p < .001$, partial $\eta^2 = .64, MSE = .03$. Namely, the majority of switches occurred within the first second of encoding ($M = 1.14, SE = .03$), and the least number of switches occurred within the last second of encoding ($M = 0.68, SE = .03$). Adding PA accuracy as a covariate revealed a significant main effect of PA accuracy, $F(1, 120) = 11.02, p = .001$, partial $\eta^2 = .08, MSE = .17$, but no interaction between PA accuracy and Bin, $F = 2.48, p = .086$. Thus, those who best learned the task demonstrated more switches overall when compared with those with low learning ability, $r = .29, p < .001$.

Correlations among all measures. Increased PA accuracy was associated with higher WMC, $r = .25, p < .01$, and higher LTM ability, $r = .69, p < .001$, on LTM measures other than PA cued recall (e.g., source memory and free recall), a result largely consistent with prior work (Miller et al., 2019; Unsworth, 2019). Note that the variable TEPR in Table 2 reflects mean pupil dilation at the last bin of the encoding period. We used the final bin because this point tended to reflect each individual's max pupil dilation during the learning period. Better PA accuracy was associated with larger TEPRs at the end of the encoding period ($r = .35, p < .001$; see Figure 6), as well as more switches between Cue and Target pairs. Neither proportion of fixations upon the Target or Cue related to mean recall accuracy (both r s $< .01$).

Regression. Given that prior work—and the correlations above—demonstrates that WMC and LTM are important for

learning, we wanted to examine whether learning ability is still related to variation in attention at encoding when taking these factors into account. Since learning related differences (as indicated by PA accuracy) were not related to viewing behavior in terms of overall time spent fixating upon the Cue or Target (see Table 2), only TEPRs and switches were entered into the simultaneous linear regression model as predictors of PA accuracy (along with WMC and LTM ability). Similar to above, the TEPR variable entered into the regression reflects mean pupil dilation at the last bin of the encoding period.

As shown in Table 3, all of the predictors together accounted for 55% of the variance in PA accuracy, $F(4, 117) = 35.32, p < .001$. Critically, both pupillary responses and switches accounted for unique variance in recall performance when taking WMC and LTM ability into account. All predictors were positively related to recall performance, meaning higher scores on these measures were associated with improved PA cued recall accuracy. Note that WMC did not predict PA accuracy with LTM in the model (because of the two constructs sharing substantial variance). Altogether, these results suggest that even when controlling for the influence of WMC and LTM ability, individual differences in attention at encoding are important in accounting for variation in learning ability.

Table 2
Correlations Between All Measures in Experiment 1

Measure	1	2	3	4	5	6	7
1. WMC	—						
2. LTM	.31***	—					
3. PAacc	.25**	.69***	—				
4. TEPR	.13	.21*	.35***	—			
5. CueFixProp	.21*	-.03	-.03	-.13	—		
6. TargetFixProp	-.06	.03	.01	.02	-.22*	—	
7. MeanSwitches	-.00	.20*	.29***	.02	.12	.14	—

Note. WMC = working memory capacity; LTM = long term memory; TEPR = task-evoked pupillary response; CueFixProp = proportions of fixations on cue; TargetFixProp = proportion of fixations on target.
* $p < .05$. ** $p < .01$. *** $p < .001$.

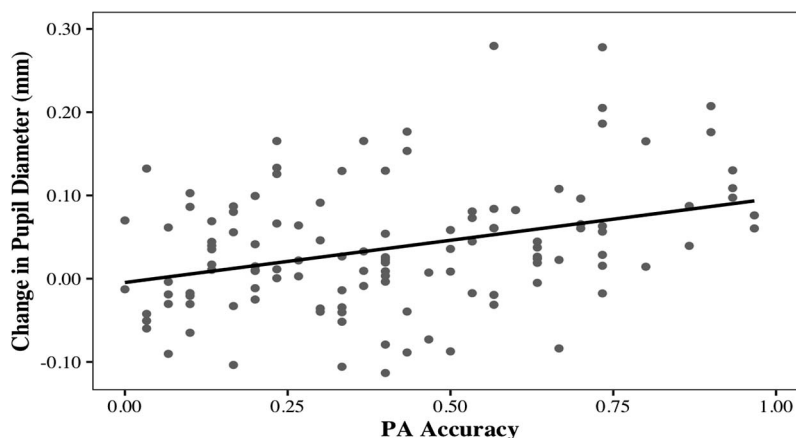


Figure 6. Scatterplot depicting relation between task-evoked pupillary responses (TEPRs) at encoding and paired associates (PA) recall accuracy in Experiment 1.

Discussion

Experiment 1 sought to determine whether variation in the ability to control aspects of one’s attention is important for learning and for variation in learning abilities. We addressed this question by first examining how individual differences in the intensity of attention impact learning ability. Using pupil dilation as an online indicator of the intensity of attention, we demonstrated that those who performed best on the PA task showed an increase in pupil dilation throughout the encoding phase of each to-be-remembered word pair. On the other hand, those who performed the worst on the PA task showed no such increase in pupil dilation at encoding. Therefore, consistent with Miller and colleagues (2019), the best learners appear to be individuals who can increase (and sustain) attention to items during encoding, whereas worse learners appear to be unable or unwilling to increase the allocation of attention at encoding.

Next, we examined whether individual differences in attentional focus are important for learning and learning ability. Using eye gaze fixations to monitor which items individuals attended to most, results revealed that neither proportion of fixations on the Target or Cue were associated with task performance. All participants tended to fixate most on the Target, followed by the Cue. We can therefore rule out the possibility that those who learn the task less well display worse performance (compared with those who better learn the task) because they neglect relevant information at study. With respect to how fixations changed across learning, all indi-

viduals first briefly fixated most upon the Cue then transitioned to fixate most upon the Target (followed by little to no differences in fixations between Targets and Cues around 1,800 ms into the encoding period). Differences in learning ability only seemed to arise in that low learning ability individuals showed a slight delay in their transition to viewing the Target compared with high learning ability individuals. Therefore, it appears that—at least in the context of verbal associative learning—learning ability does not seem to relate to which items individuals focus their attention on. Rather, differences appear to exist in terms of when individuals attend to the items.

Given that recent work suggests that alternations in eye-gaze fixations index the ability to generate relational links between items in associative learning paradigms (see Kamp & Zimmer, 2015), we also assessed whether variation in switches is yet another factor important for learning and learning ability. Consistent with Kamp and Zimmer (2015), results revealed the majority of switches occurred within the first second of encoding. Expanding on this work, our results further demonstrated that those who best learned the items demonstrated more switches overall when compared with those who did not learn the task as well. These findings are consistent with the notion that associative memory performance is best when individuals form associative links between the word pairs (Dunlosky et al., 2005; Richardson, 1998).

Finally, we sought to examine whether individual differences in attention at encoding still relate to learning ability when taking WMC and LTM ability into account. Critically, both pupillary responses and switches accounted for unique variance in recall performance when taking WMC and LTM ability into account. Taken altogether, these results suggest that individual differences in attentional factors at encoding—particularly the intensity of attention and alternations in attentional focus—are important for learning and for variation in learning abilities.

Experiment 2

Experiment 2 sought to replicate and extend the effects from Experiment 1. Specifically, considering the notion that elaborative, deep processing requires implementation of more attentional re-

Table 3
Simultaneous Regression Predicting PA Recall Accuracy

Variable	β	t	sr^2	R^2	F
TEPR	.21	3.29**	.04		
Mean switches	.17	2.59*	.03		
WMC	.04	.58	.00		
LTM	.60	8.86***	.30	.55	35.32***

Note. TEPR = task-evoked pupillary response; WMC = working memory capacity; LTM = long term memory.
* $p < .05$. ** $p < .01$. *** $p < .001$.

sources (relative to more shallow processes like rehearsal; Craik & Byrd, 1982), we examined whether the relation between the intensity of attention and learning ability is accounted for by differences in encoding strategies. That is, effective encoding strategies, such as mental imagery or sentence generation, are associated with better memory performance than ineffective encoding strategies like passive reading or rehearsal (Bailey, Dunlosky, & Kane, 2008; Bower, 1972; Dunlosky & Hertzog, 1998, 2001; Richardson, 1998; Unsworth, 2016). So, it seems possible that those who best learned the PA task in Experiment 1 may have also been using more effective encoding strategies than those who did not learn the task as well. If (a) effective encoding strategies are more resource demanding than ineffective encoding strategies and (b) the pupil dilates in response to increased attentional demands, then the observed learning related differences in TEPRs may have actually been due to differences in encoding strategies.

Strategies like mental imagery and semantic reference may be more effective because these strategies provide a means of using mediators to create item associations within each to-be-remembered word pair. Considering the notion that alternations in attentional focus may indirectly measure of the process by which relational links such as these are generated (see Kamp & Zimmer, 2015), we were also interested in examining whether fixations and switches similarly relate to encoding strategy use. Consequently, beyond trying to replicate the effects from Experiment 1, a critical point of analysis was to determine whether variation in attention and encoding strategy use share common and/or unique variance in predicting recall accuracy. To address these questions, participants completed an itemized retrospective strategy report immediately following the PA cued recall task.

Method

A total of 167 participants (67% female; age range: 18–31 years; M age = 19.42, SD age = 2.08) were recruited from the human subject pool at the University of Oregon. Twelve participants were excluded from all analyses because they either were not proficient in English, did not follow task directions, did not complete all tasks, had excessive missing pupil data, or were identified as outliers ($N = 155$). Data was collected over two academic quarters, and all participants were compensated with course credit necessary for meeting a course research requirement. The Institutional Review Board of the University of Oregon approved the procedure, and all participants were treated in accordance with ethical standards of the American Psychological Association. Participants were debriefed following the session.

WMC tasks. See Experiment 1.

LTM tasks.

Delayed free recall. For Experiment 2, we opted to use a more traditional delayed free-recall task (i.e., there was no value directed remembering manipulation at encoding). Task parameters were similar to that used in Experiment 1, except participants were presented with five word lists total, and each list contained 10 words. Words were presented onscreen for 1 s each.

Picture source recognition. See Experiment 1.

PA cued-recall task. After calibration of the eye-tracker, participants were administered a PA task similar to the task used in Experiment 1. The primary difference was that participants were administered a single list of 30 word-pairs.² And, immediately

after the final recall trial, participants completed an itemized retrospective strategy report in which they recounted which specific strategy they had used to remember each word pair (represented on-screen). Consistent with prior work (Dunlosky & Hertzog, 1998), strategy options included: (a) passive reading, (b) rote repetition, (c) sentence generation, (d) mental imagery, (e) other, (f) no strategy, or (g) tried to use a strategy, but didn't have time. Participants were only allowed to provide one response per word-pair. Ineffective strategies were characterized as passive reading and rehearsal, whereas effective strategies were characterized as interactive imagery and sentence generation. Considering that response options f and g both imply no strategy was successfully implemented—and also consistent with Dunlosky and Hertzog (1998)—these responses were collapsed into a single *No Strategy/No Time* category for analyses. The *other* strategy category was excluded from our analyses because few participants reported this option (see Table 4) and no a priori hypotheses were made as to whether these strategies would be more or less effective.

Results

Similar to Experiment 1, LTM and WMC were treated as continuous variables by creating a factor composite score for each participant via factor analysis with principal axis factoring. PA accuracy was again used as an indicator of learning ability and entered in as a covariate in a series of repeated-measures ANCOVAs. With the exception of proportion of “other” strategy use, all measures displayed adequate variability and were approximately normally distributed (i.e., skewness < 2; kurtosis < 4; Kline, 2016; see Table 4). Note, however, that mean levels of PA accuracy were considerably lower in Experiment 2 ($M = 21%$) than Experiment 1 ($M = 41%$). Despite having participants complete a longer practice list prior to onset of the single word-pair list in Experiment 2, there appeared to be a floor effect in performance for many participants. As such, participants who failed to recall a single word on the PA task ($n = 21$) were excluded from all analyses, leaving a total sample of 134 participants.³

Eye-tracking.

TEPRs. Data from each participant's left eye were used for analyses. Baseline pupil diameter and TEPRs were calculated via the same method used in Experiment 1. The pupil data for the 3-s encoding phase for each word was similarly broken down into a series of 200-ms timeframes, resulting in 15 total baseline corrected bins. Missing data points were excluded from averaging. TEPRs during the first 1,200 ms were again strongly confounded by fixations. Therefore, consistent with Experiment 1, we baseline corrected TEPRs by using 1,200 ms as our reference point and subtracted mean dilation at 1,200 ms from each ensuing bin.

Mean TEPRs were first submitted to a repeated-measures ANOVA with Bin as a within-subjects factor (nine levels). Results revealed a significant main effect of Bin, $F(8, 1072) = 3.99$, $p < .001$, partial $\eta^2 = .03$, $MSE = .001$, suggesting pupil diameter increased throughout the encoding period for each word ($M = .03$,

² This change was made to avoid potential reactivity effects associated with the use of concurrent strategy reports (see Bailey et al., 2008; Dunlosky & Hertzog, 2001).

³ The overall pattern of results remained the same when analyzing the data with the full sample.

Table 4
Descriptive Statistics and Reliability Estimates for All Measures

Measure	<i>M</i>	<i>SD</i>	Skew	Kurtosis	Reliability
Ospan	38.70	8.44	-0.84	0.51	.63
Rspan	38.22	8.78	-0.91	0.59	.69
Symspan	19.30	4.78	-0.45	-0.00	.54
DFR	0.50	0.15	0.76	1.20	.79
PA	0.21	0.22	1.52	1.53	.92
PicSource	0.77	0.14	-1.33	2.30	.94
TEPR	0.03	0.08	0.85	2.48	.94
CueFixProp	0.39	0.10	-0.66	1.73	.86
TargetFixProp	0.47	0.10	-0.13	1.66	.87
Switches	2.45	0.87	0.34	1.29	.86
PropEffectStrat	0.31	0.32	0.96	-0.36	
PropIneffectStrat	0.37	0.37	0.54	-1.34	
PropNoTimeNoStrat	0.29	0.31	0.72	-0.85	
PropOtherStrat	0.03	0.14	6.21	39.07	

Note. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; DFR = delayed free recall; PA = paired associates; PicSource = picture source recognition; TEPR = task-evoked pupillary response; CueFixProp = proportions of fixations on cue; TargetFixProp = proportion of fixations on target; PropEffectStrat = proportion of effective strategy use; PropIneffectStrat = proportion of ineffective strategy use; PropNoTimeNoStrat = proportion of no strategy use and efforts to use strategy but had no time; PropOtherStrat = proportion of other strategy use.

SE = .00). Adding PA accuracy as a covariate also revealed a main effect of PA accuracy, $F(1, 132) = 21.89, p < .001$, partial $\eta^2 = .14, MSE = .02$, suggesting individuals who best learned the task had larger TEPRs on average compared with those who worse learned the task, $r = .38, p < .001$. PA accuracy also interacted with Bin, $F(8, 1056) = 13.14, p < .001$, partial $\eta^2 = .09, MSE = .001$. As demonstrated in Figure 7A, TEPRs increased throughout the encoding period for high learning ability individuals but not for low learning ability individuals. The finding that learning related differences in TEPRs became larger across the encoding period is likewise reflected in Figure 7B. The correlation between PA accuracy and TEPRs continued to strengthen across the final seconds of encoding. Importantly, each of these effects replicate the results of Experiment 1 and suggest that variation in the intensity of attention at encoding is related to learning ability.

Because those who endorsed the use of more effective encoding strategies also displayed larger TEPRs at encoding, $r = .25, p < .01$, we next sought to examine whether effective strategy use was similarly associated with increased TEPRs within individuals. That is, when participants report using an effective encoding strategy, do they have larger TEPRs than they do when they report using an ineffective strategy? Multilevel modeling (MLM) was used to examine differences in TEPRs at encoding as a function of strategy type (Effective, Ineffective, or No Time for Strategy/No Strategy; see Table 4 for proportions of strategy use). We had no specific hypotheses about how No Time for Strategy/No Strategy might relate to TEPRs. We were merely interested in examining how these occurrences compare to effective and ineffective strategy use, especially considering these responses accounted for 29% of strategy reports—an estimate similar to the proportion of effective strategy use (31%). We opted to use MLM techniques here because a mean-based analytic technique (e.g., repeated-measures ANOVA) only uses data from participants with complete data. In

other words, participants who only reported using ineffective strategies and no strategy (but not effective strategies) would have been excluded from this analysis, leaving us with a total sample size of 50. Using MLM, we were able to leverage observations from participants that would have been excluded.

With respect to the model itself, TEPRs were nested within trials (i.e., word pairs) and subjects.⁴ Our fixed effects included the linear effect of bin, the quadratic effect of bin, strategy type (the reference group was effective encoding strategies), and the cross-level interaction between the linear effect of bin and strategy type. Results revealed that TEPRs at the beginning of the encoding period did not significantly vary as a function of strategy ($ps > .16$). Critically, though, a significant interaction between bin and strategy type emerged, suggesting the degree to which TEPRs increased at encoding depended on one’s strategy. As demonstrated in Figure 8, TEPRs across the encoding period increased most for effective encoding strategies, $b = .01, SE = .002, t(29,529.27) = 7.30, p < .001$. Whereas the use of effective encoding strategies was associated with the largest TEPRs, the use of ineffective strategies was associated with the smallest TEPRs, $b = -.006, SE = .001, t(29,527.78) = -6.45, p < .001$. TEPRs corresponding to reports of no time for strategy/no strategy mimicked ineffective strategies early in the encoding period such that TEPRs increased initially, but this increase was smaller than what was observed for effective strategies [$b = -.003, SE = .001, t(29,529.77) = -3.34, p < .001$].⁵ Note that we also tested a model including the interaction between the quadratic effect of bin and strategy type, but model comparisons revealed this model did not significantly improve model fit, $\chi^2(2) = 1.76, p > .41$; the quadratic trend did not significantly vary across strategy types ($ps > .23$). Hence TEPRs for all strategy types tended to reach asymptotic levels at the same rate ($b = -.001, SE = .000, t(29,528.79) = -3.87, p < .001$).

Fixations. Fixations were again examined as a function of Location (Cue, Target, Fixation, or Other) to better understand how attentional focus relates to recall performance in the context of verbal associative learning. ROIs were determined in the same manner as Experiment 1. Proportions of fixations were similarly obtained by first summing the number of times an individual fixated on a given object during the 3-s encoding phase. Given samples were collected every 16 ms, the number of fixations for each category were then divided by an individual’s total number of

⁴ Level 1:

$$Y_{ij} = \beta_{0ij} + \beta_{1ij}(\text{Linear}_{ij}) + \beta_{2ij}(\text{Quad}_{ij}) + e_{ij}$$

Level 2:

$$\beta_{0ij} = \gamma_{00} + \gamma_{01}(\text{Strat}_{ij}) + \mu_{0i} + \nu_{0j}$$

$$\beta_{1ij} = \gamma_{10} + \gamma_{11}(\text{Strat}_{ij})$$

$$\beta_{2ij} = \gamma_{20}$$

⁵ Examining subsequent memory as a function of strategy type via logistic MLM (with Strategy Type entered as a fixed effect, Subject and Trial as random effects, and intercepts allowed to vary) revealed the same general trend. Namely, ineffective ($\gamma = -3.18, SE = 0.18, z$ value = $-17.82, p < .001$) and no time/no strategy ($\gamma = -5.48, SE = 0.34, z$ value = $-16.19, p < .001$) were associated with worse expected log odds of subsequent recall relative to effective strategies. In other words, the odds of a participant correctly recalling an item using an effective strategy was 24.10 times greater than when they used an ineffective strategy and 239.92 times greater than when they used no strategy/tried to use a strategy but didn’t have time.

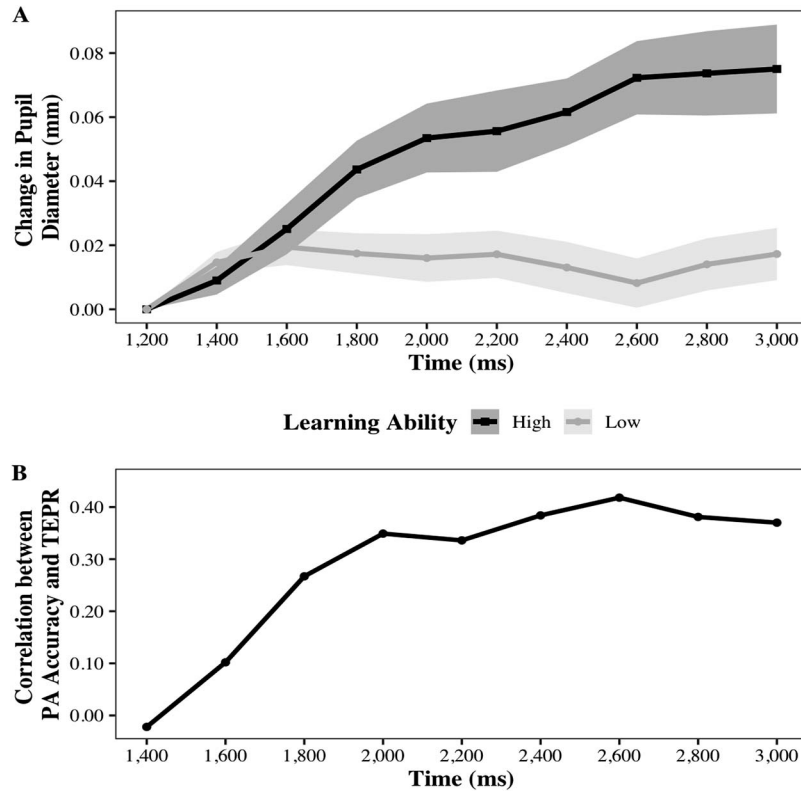


Figure 7. (A) Change in pupil diameter (mm) across the encoding period in Experiment 2 for each word-pair as a function of high ($n = 34$) versus low ($n = 47$) learning ability. Shaded areas reflect one standard error of the mean. (B) Change in correlation between paired associates (PA) accuracy and task-evoked pupillary response (TEPR) across the encoding period for each word-pair.

fixations. A 4 (Location; within-subjects factor) \times 15 (200-ms Bin; within-subjects factor) repeated-measures ANOVA revealed a main effect of Location, $F(3, 99) = 121.15$, $p < .001$, partial $\eta^2 = .79$, $MSE = .20$, suggesting participants focused most on the Target ($M = .48$, $SE = .02$), followed by the Cue ($M = .39$, $SE = .02$), Fixation ($M = .10$, $SE = .02$), and Other ($M = .03$, $SE = .01$).

A Location \times Bin interaction also emerged from the model, $F(42, 1386) = 40.95$, $p < .001$, partial $\eta^2 = .55$, $MSE = .02$. Replicating Experiment 1, participants initially fixated most on the Cue but soon (within the first second of encoding) transitioned to primarily view the Target. Interestingly, although Experiment 1 showed little to no differences in fixations between Targets and Cues across the final second of encoding, Figure 9 reveals that

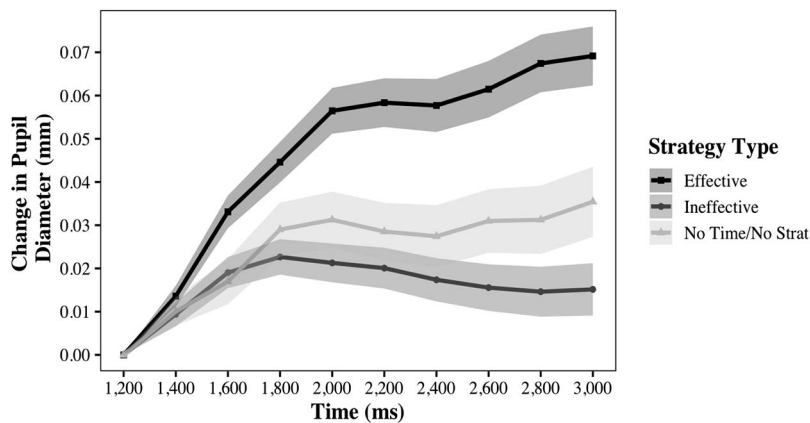


Figure 8. Changes in pupil diameter (mm) across the encoding period for each word as a function of Effective Strategies, Ineffective Strategies, and No Time for Strategy/No Strategy. Shaded areas reflect 1 SEM.

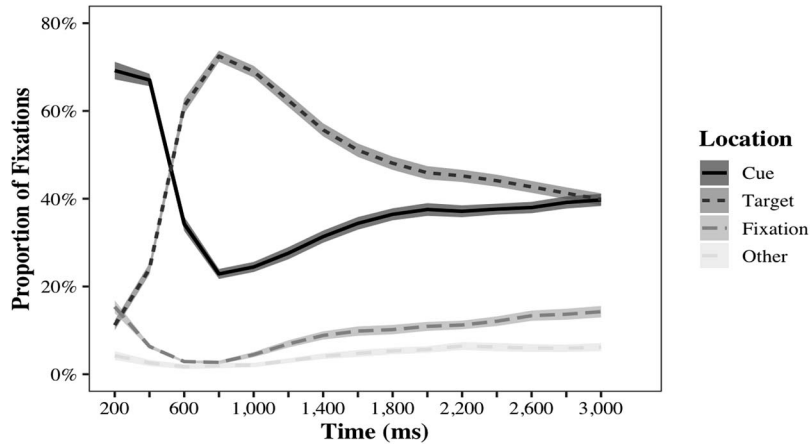


Figure 9. Proportion of fixations across the 3-s encoding period in Experiment 2 as a function of Location (Cue, Target, Fixation, and Other). Shaded areas reflect 1 SEM.

participants continued to view the Target out of proportion to the Cue throughout the remainder of the encoding period. Though, differences between the proportion of Cue and Target fixations did continue to decrease. Figure 9 further reveals that while participants spent little time viewing Central Fixation, there appeared to be an positive linear trend in proportion of fixations on Fixation during the final 2 s of the encoding period (linear trend: $F[1, 133] = 85.07, p < .001, \eta^2 = .39, MSE = .02$). Finally, as reflected by the line for *Other* locations, participants appeared to rarely fixate on anything other than the Cue, Target, or Central fixation.

Next, PA accuracy was added as a covariate to observe any possible influence of learning ability on viewing behavior. The 4 (Location; within-subjects factor) \times 15 (200-ms Bin; within-subjects factor) repeated-measures ANCOVA revealed a significant three-way interaction between Location, Bin, and PA accuracy, $F(42, 5544) = 2.93, p < .001, \text{partial } \eta^2 = .02, MSE = .01$. Figure 10 demonstrates that both high and low learning ability individuals first briefly fixated most upon the Cue then transitioned to fixate most upon the Target (followed by little to no

differences in fixations between Targets and Cues in the final second of the encoding period). Learning related differences appear to be driven by low learning ability individuals having less fixations than high learning ability individuals when Cue and Target fixations reach peak viewing time.

Switches. Switches were calculated in the same manner as Experiment 1, and mean switches were again obtained for each second of the encoding period. Consistent with both Experiment 1 and other prior research (Kamp & Zimmer, 2015), a repeated-measures ANOVA with Bin (1 s; three levels) as a within-subjects factor revealed a significant effect of Bin, $F(2, 266) = 261.24, p < .001, \text{partial } \eta^2 = .66, MSE = .03$. Most switches occurred within the first second of encoding ($M = 1.10, SE = .03$), whereas the least switches occurred within the last second of encoding ($M = 0.64, SE = .03$). Contrary to Experiment 1, however, when PA accuracy was added as a covariate no effects of PA accuracy emerged ($F_s < 1.10, p_s > .33$). Thus, learning ability in Experiment 2 was unrelated to mean switches, $r = .06, p = .519$.

Correlations among all measures. As demonstrated in Table 5, increased PA accuracy was associated with greater WMC, $r =$

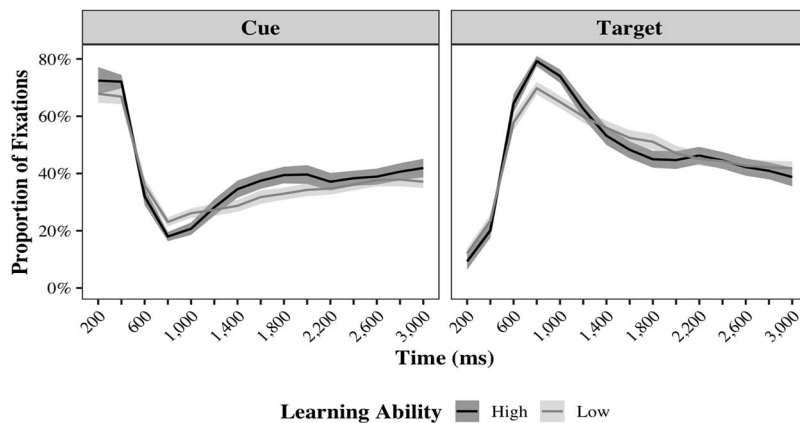


Figure 10. Proportion of fixations across the 3-s encoding period as a function of Location (Cue vs. Target) for high ($n = 34$) versus low ($n = 47$) learning ability individuals.

Table 5
Correlations Between All Measures in Experiment 2

Measure	1	2	3	4	5	6	7	8	9
1. WMC	—								
2. LTM	.23**	—							
3. PAacc	.20*	.38***	—						
4. TEPR	.09	.10	.37***	—					
5. CueFixProp	.01	.09	.08	-.06	—				
6. TargetFixProp	-.02	.02	-.02	.24**	-.32***	—			
7. MeanSwitches	.07	.11	.06	-.16	.37***	-.11	—		
8. EffectiveStrat	.07	.31***	.78***	.25**	.01	-.10	-.04	—	
9. IneffectiveStrat	-.02	-.18*	-.48***	-.22**	-.04	.04	.06	-.56***	—

Note. WMC = working memory capacity; LTM = long term memory; TEPR = task-evoked pupillary response; CueFixProp = proportions of fixations on cue; TargetFixProp = proportion of fixations on target.
* $p < .05$. ** $p < .01$. *** $p < .001$.

.20, $p < .05$ and greater LTM ability, $r = .38$, $p < .001$. Critically, we further replicated the results from Experiment 1 in that better PA accuracy was also associated with larger TEPRs at encoding (see Figure 11). The mean number of switches during learning, however, was unrelated to PA accuracy, a result inconsistent with Experiment 1. In regard to strategy use, effective strategy use demonstrated a positive relation with both PA accuracy, $r = .78$, $p < .001$ and TEPRs, whereas ineffective strategy use demonstrated a negative relation with both PA accuracy, $r = -.48$, $p < .001$ and TEPRs, $r = -.22$, $p < .01$. Neither effective nor ineffective strategy use were associated with eye gaze fixations or switches. Strategy use therefore appears to only relate to variation in the intensity of attention.

Regression. First, we wanted to examine whether we could replicate Experiment 1's finding that learning ability is related to variation in attention at encoding even when accounting for WMC and LTM ability. Like Experiment 1, the TEPR variable entered into the regression reflects mean pupil dilation at the last bin of the encoding period. Note, however, that because mean switches did not correlate with PA accuracy in Experiment 2, they were excluded from the model. Also, given that a major point of interest in Experiment 2 was to determine whether strategy use accounts for the relation between TEPRs and recall performance, proportion of effective strategy use was added to the model.

Table 6 shows that, together, TERPs, WMC, LTM ability, and effective strategy use accounted for 67% of the variance in PA accuracy, $F(4, 129) = 66.06$, $p < .001$. All predictors accounted for significant unique and shared variance in PA accuracy, with increases in each of the predictors associated with increased recall performance.⁶ The intensity of attention (as indexed via TEPRs) accounted for unique variance in recall performance even when taking WMC, LTM ability, and effective strategy use into account. Indeed, whereas a partial correlation analysis revealed that the zero-order correlation between TEPRs and recall dropped when controlling for shared variance with effective strategy use (partial $r = .29$, $p = .001$), the relationship between TEPRs and recall remained significant.

Discussion

Using a verbal PA cued recall task and a retrospective itemized strategy report, Experiment 2 tested the notion that variation in

attentional abilities at encoding may reflect differences in encoding strategy use. The results revealed a number of findings. First, consistent with prior research (Ariel & Castel, 2014; Miller et al., 2019; Papesch et al., 2012), as well as Experiment 1, increased allocation of attention to items at encoding (indexed via TEPRs) was associated with better memory performance and variation in learning ability. Pupil dilation continued to increase throughout the encoding period for those who scored best on the PA task, whereas little to no change in pupil dilation was observed for those who scored the worst.

Further replicating previous work (Dunlosky & Hertzog, 1998, 2001), effective encoding strategy use was also associated with superior associative memory performance. Expanding on this research, we further revealed that effective encoding strategies were positively correlated with TEPRs at encoding, suggesting those who endorsed the use of more effective encoding strategies allocated more attentional resources to to-be-remembered word pairs. MLM analyses further revealed that effective strategy use was similarly associated with both superior subsequent memory and increased pupil dilation within individuals. The increase in TEPRs across the encoding period was largest when participants reported using effective encoding strategies, rather than ineffective or no strategies. These results are widely consistent with the idea that encoding strategies characterized by more elaborative processing require more attentional resources than do strategies characterized by shallower processing (Craik & Byrd, 1982). Critically, whereas effective encoding strategy use partially accounted for the relation between the intensity of attention and PA accuracy, the intensity of attention (as indexed via TEPRs) continued to account for unique variance in PA accuracy even when taking effective strategy use, WMC, and LTM ability into account.

With respect to attentional focus, neither the overall proportion of fixations on the Cue or Target correlated with PA recall accuracy. All participants first briefly fixated most upon the Cue then transitioned to fixate most upon the Target, with differences be-

⁶ Note that compared with Experiment 1, LTM ability explains substantially less unique variance in PA accuracy. This is likely attributable to shared variance with effective strategy use. Indeed, when controlling for effective strategy use, the correlation between LTM ability and PA accuracy drops to .24 ($p = .006$).

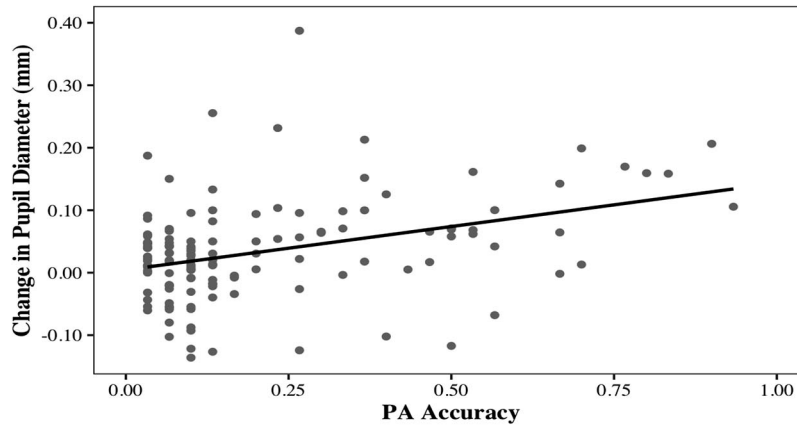


Figure 11. Scatterplot depicting relation between task-evoked pupillary responses (TEPRs) at encoding and paired associates (PA) recall accuracy in Experiment 2.

tween Target and Cue fixations continuing to diminish throughout the remainder of the encoding period. Learning-related differences arose such that when participants transitioned to predominantly view the Target (around 600 ms to 1,200 ms into the encoding period), low learning ability individuals continued to view the Cue more than high learning ability individuals. However, while the majority of switches again occurred within the first second of encoding, learning ability was not related to the number of switches during encoding. These results, therefore, are the first to suggest that variation in attention—particularly the intensity of attention—during encoding is an important, unique contributor to individual differences in learning.

General Discussion

In two experiments, we examined how two critical aspects of attention relate to learning ability on a verbal PA cued recall task. We first sought to examine whether individual differences in the intensity of attention and variation in attentional focus impact learning ability. If such relations exist, we then sought to determine whether variation in attentional abilities at encoding still relate to learning when taking WMC and LTM ability into account. Finally, we wanted to assess what role encoding strategies may play in these relationships, especially in terms of the relationship between the intensity of attention and learning ability. Pupillary responses were used as an online indicator of the intensity of attention, whereas eye gaze fixations provided a means of monitoring one’s attentional focus.

In both experiments, there were substantial individual differences in pupillary responses at encoding. High learning individuals demonstrated stronger pupillary dilations than low learning individuals. In fact, whereas the high learning individuals demonstrated a strong linear increase in TEPRs during learning, low learning individuals did not demonstrate a significant pupillary response during learning. Although prior work suggests these increases in intensity may be at least partially attributable to differences in overall attentional capacity whereby high capacity individuals can allocate more attention to learning than low capacity individuals (Miller et al., 2019), increases in intensity could also be attributed to increases in motivation whereby individuals who are more motivated to do well on the task allocate a greater proportion of their attentional resources to learning than low motivated individuals. By way of illustration, an individual may have plenty of excess capacity but is not sufficiently motivated to perform well on the task, thereby not allocating much of their capacity to learning and resulting in poor performance. Alternatively, some individuals might have reduced capacity but are sufficiently motivated to perform well, in which case they might allocate most of their available resources to learning. Or, rather than an issue of motivation per se, it’s also possible that in being aware of one’s limitations, one may similarly devote less available resources to the task at hand if they believe they are incapable of successfully performing the task. Unfortunately, though, the present study did not include any assessments of self-reported levels of motivation or self-efficacy, leaving these important considerations for future research.

Although motivation likely accounts for some of the variance attributed to TEPRs, a purely motivational account would seemingly suggest that individuals who are dispositionally more motivated to do well in general would not only allocate a greater proportion of their attentional resources to encoding (i.e., larger TEPRs), but they would also display better performance across the board (e.g., use more effective encoding strategies, score higher on WMC, and score higher on the other LTM tasks). As such, substantial shared variance should exist across all of these constructs when predicting PA recall accuracy. In both experiments, however, pupillary responses were unrelated to WMC. In addition, both experiments revealed that TEPRs continued to predict unique

Table 6
Simultaneous Regression Predicting PA Recall Accuracy

Variable	β	t	sr^2	R^2	F
TEPR	.17	3.32**	.03		
WMC	.11	2.07*	.01		
LTM	.13	2.31*	.01		
Effective strat use	.69	12.67***	.41	.67	66.06***

Note. TEPR = task-evoked pupillary response; PA = paired associates; WMC = working memory capacity; LTM = long term memory.
* $p < .05$. ** $p < .01$. *** $p < .001$.

variance in PA accuracy, even when taking into account the other above-mentioned constructs. Taken altogether, we do not believe motivation alone could account for the main conclusions of the article. It is likely that the intensity of attention, as indexed by TEPRs, is a multiply determined construct.

Indeed, there are several other possible variables that could influence individual differences in the intensity of attention that have a subsequent impact on individual differences in learning. Experiment 2 further revealed that encoding strategies modulate the intensity of attention, such that effective encoding strategies were associated with larger TEPRs relative to ineffective and no strategies. Notably, regression analyses indicated that effective encoding strategy use only partially accounted for the relation between the intensity of attention and PA recall accuracy, meaning the intensity of attention (as indexed via TEPRs) continued to account for unique variance in PA accuracy even when taking effective strategy use, WMC, and LTM ability into account. These results are consistent with more recent work suggesting the amount of available resources at encoding impacts other types of processing than just those associated with effortful strategic processing (see Naveh-Benjamin & Brubaker, 2019). Future research should try to identify the remaining variables important for modulating the intensity of attention, for example motivation, self-efficacy, persistence, alertness, or task goals.

The findings discussed thus far provide initial evidence that individual differences in the intensity of attention are a unique and critical source of variation in learning ability. With regard to what role attentional focus may play in learning, results from both experiments revealed that neither the overall proportion of fixations on the Cue or Target was associated with memory performance. All participants tended to fixate most on the Target, followed by the Cue. An examination of fixations over the course of the learning period revealed all individuals first briefly fixated most upon the Cue then transitioned to fixate most upon the Target (followed by continuously diminishing differences between Target and Cue fixations throughout the final second of encoding). Differences in learning ability only seemed to arise when considering the timing of fixations. That is, in Experiment 1, low learning individuals demonstrated a slight delay in their transition to viewing the Target. In Experiment 2, however, low learning individuals appeared to view the Target less than high learning individuals only when peak viewing occurred for the Target. It appears that—at least in the context of verbal associative learning—learning ability does not relate to which items individuals focus their attention on overall. Rather, differences appear to exist only when considering when individuals attend to relevant items. We can therefore rule out the possibility that those with low learning ability merely neglect relevant information during study. Considering that fixations did not relate to encoding strategy use, future work should aim to better elucidate reasons for which learning related differences exist in terms of when individuals focus on relevant items during encoding.

Finally, we also examined alternating attentional focus by monitoring the number of switches (alternations in eye gaze fixations) during learning. Consistent with prior work (Kamp & Zimmer, 2015), both experiments revealed the majority of switches occurred within the first second of encoding. Kamp and Zimmer (2015) suggested that these alternations in atten-

tional focus may reflect the process by which individuals generate relational links (aka mediators) between items in associative learning paradigms. Considering associative memory performance is best when individuals form relational links between word pairs (Dunlosky et al., 2005; Richardson, 1998), a critical point in analysis was to examine whether variation in switches also relates to learning ability. Indeed, Experiment 1 showed that those who best learned the task demonstrated more switches overall when compared with those who did not learn the task as well. Switches even explained unique variance in PA recall accuracy when taking into account WMC, LTM ability, and TEPRs.

Despite these results providing evidence that individual differences in attentional focus—particularly variation in alternating attentional focus—are also important in predicting learning ability, Experiment 2 revealed that switches were unrelated to effective strategy use, a particularly surprising result given effective strategies presumably provide a means of using mediators to create item associations within each to-be-remembered word pair. Of course, two individuals can both report using an effective strategy like mental imagery, but the degree to which the mediators generated by these individuals successfully bind items can differ. It therefore seems possible that switches may more so reflect the success with which mediators bind relational features between associative pairs. Unfortunately, though, Experiment 2 also failed to replicate the positive relation between switches and memory performance. Admittedly, we do not have a good explanation as to why the relationship between switches and performance was not found in Experiment 2. It could be the case that switches are not necessary for successful generation of item associations, or perhaps switches do not actually reflect the process of generating mediators between items. Yet another possibility is that the difficult nature of our task could have obscured any effect. While prior work has similarly administered a single, long list of word-pairs in PA cued recall (e.g., Bailey et al., 2008), mean proportion correct in our second experiment ($M = .21$, $SD = .22$) was substantially lower than performance in Experiment 1 ($M = .41$, $SD = .26$). Future research could try to better replicate the effects observed in Experiment 1 by using multiple long word-pair lists in conjunction with strategy reports.

It is widely accepted that attention is important for learning, but until now it has not been clear whether individual difference in attentional factors at encoding are important for learning and variation in learning ability. By examining (a) the intensity of attention with pupillary responses and (b) attentional focus/alternations in attentional focus with eye gaze fixations/switches, the present investigation presents new evidence for the notion that substantial and robust individual differences exist in attentional abilities at encoding—abilities that are essential for successful learning. The best learners appear to increase (and sustain) attention to items during encoding, which is partially accounted for by their use of more effective encoding strategies. Those with the best learning ability may also be better able to alternate attentional focus, seemingly reflecting an enhanced ability to generate relational links (aka mediators) between word pairs. On the other hand, while we ruled out the possibility that worse learners obtain inferior performance because they ignore or attend less to relevant information, these individuals are seemingly unable or unwilling to increase the allocation of attention during encoding. Together

these results suggest that attentional abilities at encoding need to be taken into consideration when trying to elucidate reasons for which individuals differ in learning ability.

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