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Monitoring the ebb and flow of attention: Does controlling the onset of stimuli during encoding enhance memory?

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Abstract

Central to the operation of the Atkinson and Shiffrin's (*Psychology of learning and motivation, 2*, 89-195, 1968) model of human memory are a variety of control processes that manage information flow. Research on metacognition reveals that provision of control in laboratory learning tasks is generally beneficial to memory. In this paper, we investigate the novel domain of attentional fluctuations during study. If learners are able to monitor attention, then control over the *onset* of stimuli should also improve performance. Across four experiments, we found no evidence that control over the onset of stimuli enhances learning. This result stands in notable contrast to the fact that control over stimulus offset does enhance memory (Experiment 1; Tullis & Benjamin, *Journal of memory and language, 64* (2), 109-118, 2011). This null finding was replicated across laboratory and online samples of subjects, and with both words and faces as study material. Taken together, the evidence suggests that people either cannot monitor fluctuations in attention effectively or cannot precisely time their study to those fluctuations.

Keywords memory · metamemory · attention · recognition

Introduction

The groundbreaking paper by Atkinson and Shiffrin (1968), to which this special issue is a salute, is famous for many things. First and foremost, it explicitly defined three systems that make up human memory: sensory memory, short-term memory, and long-term memory. That characterization continues to be predominant today, omnipresent in student textbooks as well as journal articles. Second, it defined ways in which information flows from one system to the next. In this article, we focus on the maintenance and transfer of information, and, critically, on the role of self-deployed control processes in guiding information flow. The role of the Atkinson and Shiffrin (1968) chapter in initiating discussion of the control processes underlying encoding and remembering is somewhat underappreciated. In fact, the model is often referred to in shorthand as the *multistore* model of memory, a nickname that probably reflects the preference within cognitive psychology for the tidy division of boxes over the messy proliferation of arrows. This state of affairs was aptly recognized by Atkinson and Shiffrin (1968):

> Since subject-controlled memory processes include any schemes, coding techniques, or mnemonics used by the subject in his effort to remember, their variety is virtually unlimited and classification becomes difficult. (p. 106)

Indeed, the project of classifying and taxonomizing control processes has made fitful progress over the years. That difficulty notwithstanding, there is a vibrant and relevant literature on the *metacognitive control of learning and remembering* that owes a great debt to the original formulation of control processes as those that facilitate transfer of information into progressively more well learned states of knowledge (for reviews, see Benjamin (2007); Fiechter, Benjamin, & Unsworth (2016); Kornell & Finn (2016), Son & Metcalfe (2000)).

Within the Atkinson and Shiffrin (1968) framework, the control that individuals exert directly impacts the formation and strength of memory traces. Once information enters short-term memory, different forms of rehearsal either "maintain" access to that information without commitment to long-term memory, or transfer that information into long-term memory. Moreover, because short-term memory is limited in capacity,

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individuals make decisions about what will enter short-term memory and what can be discarded. Overall, individuals have a wide range of freedom when controlling information in short-term memory. Individuals can also implement control processes that determine what information from sensory memory enters short-term memory and also how that information will be stored in long-term memory. Nonetheless, more effort in research on memory has been spent on devising paradigms in which sources of individual variation in learning are controlled than in understanding the consequences of that variation.

In the current literature on metacognitive control, the emphases are somewhat different. Less attention is paid to the question of where knowledge resides than to its durability. And, the study of metacognition is not driven by major overarching theoretical perspectives on the structure of memory – in fact, theoretical development within the study of metacognition is mostly divorced from theoretical development in memory. This is an unfortunate state of affairs. As Atkinson and Shiffrin (1968) rightly pointed out, the structure of memory dictates the types of relevant control processes. And any theory of memory is incomplete without acknowledgment and an explicit characterization of motivations, intentions, and capacities of the learner. It is like trying to understand a system of roadways without knowing about traffic.

Modern research on the metacognitive control of learning focuses on two questions: (1) Does utility of self-control improve performance? (2) How do learners monitor progression towards learning goals and select learning strategies appropriate for those goals? These are the empirical and theoretical agendas, respectively, for the domain of metacognition control. The research we report here addresses a novel theoretical question: Can learners monitor fluctuations in attention and synchronize encoding events to those fluctuations? In doing so, we explore a novel empirical domain: Does having control over the *onset* of to-be-learned materials improve memory for those materials? For background, we briefly review two relevant domains: fluctuations in attention, and control over the timing of study events.

Fluctuations in attention

Control over when to view study items can benefit learners by timing stimuli to moments of focused attention. Attention is always fluctuating over time, flowing between states of internal and external focus (e.g., Desimone & Duncan, 1995; Posner & Petersen, 1990; Treisman & Gelade, 1980). Moments of internally focused attention, commonly described as *mind wandering*, can decrease memory on various tasks that require external focus, seen empirically in decreased reading comprehension (Dixon & Bortolussi, 2013; Feng, D'Mello, & Graesser, 2013; Franklin, Smallwood, & Schooler, 2011; Jackson & Balota, 2012; Kane and McVay,

2012; Smallwood, McSpadden, & Schooler, 2008; Unsworth & McMillan, 2013) and retention of classroom lectures (Farley, Risko, & Kingstone, 2013; Szpunar, Khan, & Schacter, 2013). Using reaction time (RT) as an indicator of attention on a sustained attention task, deBettencourt, Norman, and Turk-Browne (2018) investigated the direct costs of attention fluctuations on subsequent memory. The task required participants to view a series of pictures and respond "yes" to targets and "no" to non-targets. The categories of indoor and outdoor pictures were counterbalanced across participants, with targets being members of the infrequent category (e.g., outdoor pictures) and occurring 10% of the time. Non-targets were from the frequent category (e.g., indoor pictures) and appeared 90% of the time. The authors hypothesized that, in general, faster responses reveal lapses in external focus (deBettencourt, Cohen, Lee, Norman, & Turk-Browne, 2015; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Consistent with this claim, memory for target items that were preceded by faster RTs was worse than memory for those preceded by slower RTs. This result suggests that lapses in attention have predictable downstream costs on memory, and supports the notion that control over the onset of study material should benefit learners. Learners will benefit from such control to the degree that they can successfully monitor fluctuations in attention and time the presentation of stimuli to them.

Controlling the timing of study events

Learners allocate study time in a manner consistent with the expected demands on retrieval and on their goals. Instructions to emphasize accuracy over speed increase study time across the board (Dunlosky & Thiede, 1998). They also spend more time on a list if they expect a (difficult) free-recall test than an (easier) cued-recall test (Finley & Benjamin, 2012). These study policies apply to individual memoranda as well: Learners selectively spend more time studying difficult items when expecting free recall (in this case, when compared to recognition; Mazzoni & Cornoldi, 1993). In general, learners choose to restudy difficult materials over easy ones (Son & Metcalfe, 2000), indicating that they may be trying to achieve a particular criterion level of learning for each item (Le Ny, Denhiere, & Taillanter, 1972). However, this effect is reversed when test standards are relaxed (Dunlosky & Thiede, 1998) or when each individual study event is short (Son & Metcalfe, 2000).

Study time is, unsurprisingly, also affected by the likelihood that the item will be tested. Items that are less likely to be on the test are studied for shorter amounts of time (Dunlosky & Thiede, 1998). This differential allocation of study time is more effective in simultaneous presentation than in sequential presentation (Middlebrooks & Castel, 2018). Thus, both expectations and the format of the to-be-learned

information constrain the ways in which subjects adapt their study strategy.

There are two extant theories of how learners choose to allocate their time to study material, and one new theory introduced here. According to the *discrepancy reduction* view, individuals cease studying an item when it has reached a certain criterion of learning (Dunlosky & Thiede, 1998). Criteria vary across individuals and can change depending on the context. According to this theory, items of higher difficulty will take longer to reach criterion, leading to longer study times. In contrast, the *region of proximal learning* view suggests that people focus on items that are within their grasp of being immediately learned and monitor the rate of return of ongoing study (Metcalfe & Kornell, 2003). Perseverance on study items depends on the amount of information gained per time unit of study. When the rate of return falls below a certain threshold, study ceases. The rate of return is high for easy items but quickly reaches a plateau, whereas more difficult items take longer to reach that plateau. Both theories predict that more time will be spent on harder items.

In the current studies, we consider the hypothesis that learners monitor inherent and unavoidable fluctuations in attention, and that variations in study time in part reflect controlled perseverance through dips in attention. According to this view, the finding that learners spend more study time on difficult materials may reveal that those materials elicit greater disengagement of attention. Evidence suggests that difficult reading material elicits more mind wandering than easy reading material (Feng, D'Mello, & Graesser, 2013). Of course, nothing about this hypothesis speaks against either of the theoretical viewpoints listed above; learners may well monitor ongoing learning (or rate of learning) and also perseverate through lapses of attention.

Effectiveness of self-directed learning

In general, giving learners control over aspects of study improves learning and memory (Fiechter et al., 2016; Finley, Tullis, & Benjamin, 2010). This is true for control of restudy opportunities (Kornell & Metcalfe, 2006), for control of category learning (Markant & Gureckis, 2014), and for control over the duration of study (Tullis & Benjamin, 2011). It is the latter result that is closest to the paradigm we develop here, so we describe it in more detail. Tullis and Benjamin (2011) compared memory for words in a group of subjects who determined how long to spend on each word with a yoked control that had the same total study time and did not control the pace of presentation. They also included a condition (in Experiment 2) in which the display duration varied across items according to an algorithm designed to maximize retention. In both cases, the group that exerted control over the pace of presentation outperformed all other groups. Similar benefits of self-pacing have been found in other stimulus domains such

as faces (Tullis, Benjamin, & Liu, 2014) and paired associates (Koriat, Ma'ayan, & Nussinson, 2006). Interestingly, the benefit of self-pacing is conditional upon the strategy implemented. Only subjects who spent more time on normatively difficult items benefited from the freedom to self-pace (Tullis & Benjamin, 2011). The freedom accompanying self-paced learning provides an opportunity for learners to adopt a variety of study strategies, some of which are apparently more fruitful than others.

One way of thinking about these results is that learning is enhanced when learners control the *offset* of learning events. This enables them both to continue study to a desired criterion level and to "ride out" lapses of attention. In the current experiments, we give subjects control over the *onset* of learning events. If learners who control the duration between learning events achieve superior performance over a yoked control, then it would more strongly implicate an ability to monitor fluctuations in attention and adjust study pacing accordingly. Because learners in these experiments are only controlling the time in which the memoranda are *absent*, it is unlikely (or less likely) that they are monitoring ongoing learning with respect to a criterion.

There is one finding in the literature that suggests that control over onsets may be valuable in controlling learning. Markant, DuBrow, Davachi, and Gureckis (2014) demonstrated that control over the shifting of windows within a spatial self-exploration task (Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011) enhanced learning relative to a passive control. Perceived control over learning environments has been linked to enhanced memory through interaction between the striate and the hippocampus (Murty, DuBrow, & Davachi, 2015). The advantage of control has also been characterized as key to the benefit of active learning (Markant, Ruggeri, Gureckis, & Xu, 2016). In the present studies, we employ a different yoked control group and apply a similar logic to simple list-learning paradigms.

Experiment 1

Experiment 1 compares memory for subjects with and without control over study material. Those who were given control, had the freedom to determine the onset or offset of item presentation. Control over the offsets of study memoranda was included to ensure that the results of Tullis and Benjamin (2011) generalize to a population recruited over the Internet, to deployment of the procedure over the Internet, and to small differences in materials. Figure 1 demonstrates the paradigm used for this experiment. We directly compare this self-pacing group to the same yoked control used in Tullis and Benjamin (2011) and also to a new group that controls the onsets of study words and is also yoked to the self-pacing group.
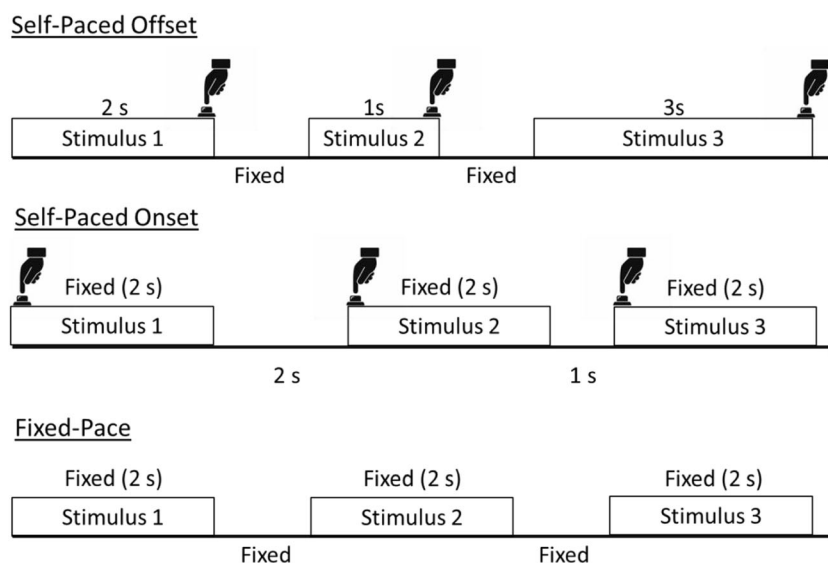
Fig. 1 Visualization of the design of Experiment 1 for one triad of participants. Subjects in the self-paced offset condition had control over the duration of the stimuli presentation. In this example, the self-paced offset subject studied the first stimulus for 2 s, the second stimulus for 1 s, and the third stimulus for 3 s. Study times were yoked such that study time was equated across triads. Subjects in the self-paced onset and fixed-paced conditions saw each stimulus for 2 s because this was the average time spent on each stimulus for the self-paced offset condition. Subjects in the self-paced onset condition were given the freedom to choose when the stimuli appeared, allowing them to make the study phase longer or shorter than the other conditions

Participants

Three hundred and fourteen participants were collected using Amazon Mechanical Turk and compensated US$1 for their time. Fourteen subjects in the fixed-rate condition were excluded because they left the experiment window and missed trials during the study phase. Subjects who were dropped were re-collected and yoked to same self-paced offset subject. The final dataset consisted of 300 subjects, 100 per condition (age: 19–71 years; gender: 165 female, 131 male, one other, and three did not respond; race: 23 Asian, 31 Black, 241 White, four other, and one did not report). Planned sample size was based on a power analysis using the effect size between self-pacing offset and fixed-pace conditions reported in Tullis and Benjamin (2011). For this simulation, two groups of data were simulated based on a normal distribution separated by an effect size of 0.45. Values from this normal distribution were logistically transformed to generate values between 0 and 1. These values represented population hit rates for individuals on the recognition test. Those individual hit rates were used as binomial probability to stimulate success on 80 trials to simulate binomial variability with a study list of this length. The sample hit rate for each simulated subject was computed as the mean of the simulated data. The two groups were then compared using a t-test and the associated p-value was stored. This was repeated 1,000 times for each sample size from 100 to 400. Power was calculated as the probability of obtaining $p < .05$ in the 1,000 simulations. A sample size of 300 (100 per condition) provided 80% power.

Materials

Subjects studied 80 of 160 concrete nouns selected from the MRC Psycholinguistic Database (Wilson, 1988). The remaining 80 words were used as distractors in the recognition test. The 160 words ranged on measures of familiarity (range: 252–645, mean = 527.52, SD = 81.83), concreteness (range: 330–641, mean = 507.98, SD = 62.31), and imaginability (range: 324–632, mean = 535.91, SD = 65.15). Materials and data are available online via Open Science Framework (https://osf.io/pt4fc/). For each triad of subjects, 80 studied words were randomly selected and presented to serve as the study items. All 160 items were used on the test. Both lists were randomized for each triad, but the order of the words in the study and test lists was identical for subjects within that triad. An additional four words were included at the beginning and end of the list to serve as primacy and recency buffers. These items were not included in the analysis and were the same for all participants.

Design

This experiment used a 3 (self-paced offset vs. self-paced onset vs. fixed-rate) between-group design. Item study times for subjects in the self-paced onset and fixed-rate conditions were yoked to subjects in the self-paced offset condition, as detailed below.

Procedure

Subjects were run online using Amazon Mechanical Turk. Once a subject completed the self-paced offset condition, subsequent subjects for that triad were randomly assigned to the self-paced onset or fixed-pace condition. This pattern continued until 100 triads of subjects were collected. All subjects were instructed to study 80 words for a later test. Subjects in the self-paced offset condition were able to control the offset of the words. Each word appeared on the screen until the subject pressed the spacebar. Once the spacebar was pressed, the word disappeared, and the screen was blank for 1 s before the next word appeared. Thus, the duration of the word display was under subject control, but the time spent between each word was fixed. Once all 80 words were presented, the average time spent on the 80 studied words was calculated and used as the study time for each word for subjects in the self-paced onset and fixed-rate conditions. The total time spent on words is thus identical across the yoked groups but distributed differently. Subjects in the self-paced onset condition were able to control the onset of each word. The screen remained blank until the subject pressed the space bar to view the next word. In the fixed-pace condition, the time between words was fixed at 1 s. Subjects in the fixed-rate condition did not have control over either the onset or offset of the study material. Figure 1 indicates the pattern of yoking across these conditions.

A word is in order about the choice of control group. In other work, yoked control subjects experience the exact same sequence and timing of events as those in self-directed groups (e.g., Markant & Gureckis, 2014). Such a procedure is in some sense a "truer" yoke. However, in list learning, we have found in previous work that variable and unanticipated offsets of words actually impair learning relative to a control group that views words displayed for equal durations. Consequently, we chose to use this control to ensure that the benefits of self-control are not simply due to the jarring nature of uncontrolled onsets and offsets of memoranda.

After studying the list of words, all subjects completed a 30-s distractor task where they did simple arithmetic. Then all subjects were given a recognition test. The recognition test consisted of 80 old words that were studied previously and 80 new words that were not presented in the study phase. Subjects were told to identify if the word presented was old or new, and gave confidence judgements on a scale from 1 to 4 with (1) "I am certain I have not seen that word," (2) "I think I have not seen that word," (3) "I think I have seen that word," and (4) "I am certain I have seen that word". These confidence judgements allow d_a to be calculated, a measure of discrimination that is based on the unequal-variance signal-detection theory (Green & Swets, 1966).

Results

Statistics reported here using null hypothesis significance testing (NHST) use the significant level of alpha < .05. Bayes factors (BF_{10}) are reported using the non-informative Jeffreys prior on the variance of the normal population and a Cauchy prior on the standardized effect size ($r=0.707$), and are only considered probative if $BF_{10} > 3$ or $BF_{10} < 0.3$ (Jeffreys, 1961; Rouder, Morey, Speckman, & Province, 2012).

Condition analysis Mean hit and false alarm rates for subjects are reported in Table 1. Six subjects were removed from analysis due to an inability to calculate d_a from their confidence ratings: four in the fixed-pace condition, one in the self-paced offset condition, and one in the self-paced onset condition. This difficulty arises when subjects do not use a sufficient number of cells within the confidence scale.

Replicating Tullis and Benjamin (2011), self-paced offset subjects exhibited higher discriminability ($M = 1.17$, $SD = 0.79$) than fixed-pace subjects ($M = 0.88$, $SD = 0.68$, $t(93)=2.78$, $p = .007$, $BF_{10} = 4.21$). However, the self-paced onset condition ($M = 1.02$, $SD = 0.80$) did not lead to higher discriminability than either the self-paced offset ($t(93) = 1.35$, $p = .180$, $BF_{10} = 0.27$) or fixed-pace conditions ($t(93)=1.30$, $p = .196$, $BF_{10} = 0.26$). In both of these latter cases, the evidence favored the null hypothesis.

Relationship between metacognitive control and memory
For subjects in the self-paced offset condition, we investigated the relationship between self-paced study time and the hit rate for each word. We did this on a subject-by-subject basis so as to deconfound the large individual differences in study time and memory. Average McFadden's R^2 for logistic regression across subjects was larger than 0 ($M = 0.03$, $SD = 0.05$, $t(99) = 4.90$, $p < .001$, $BF_{10} = 3,898.72$), indicating strong evidence for a small positive relationship between study time and memory. A similar analysis was conducted for self-paced onset subjects to evaluate whether the time spent before or after the word influenced the probability of a hit on the recognition test. Regression coefficients were reliably but only slightly greater than 0 for time spent before ($M = 0.02$, $SD = 0.03$, $t(99) = 6.94$, $p < .001$, $BF_{10} = 2.3 \times 10^7$) and after ($M = 0.02$, $SD = 0.03$, $t(99) = 5.71$, $p < .001$, $BF_{10} = 102,498.9$). Results from these models indicate that the timing of study is related to memory, but it is impossible to deconfound the effects of individual word characteristics in this relationship.

The timing of material for each subject in the self-paced offset and self-paced onset conditions is shown in Fig. 2, and provides a visualization of individual differences in pacing strategies. Subjects who took a longer total time to encode the list achieved higher discriminability in the self-paced offset condition ($r(97) = .53$, $p < .001$, $BF_{10} = 1.03 \times 10^6$). Evidence for this relationship

Table 1 Percentage of hits and false alarms (and standard deviations) for all four experiments

	Hits	False alarms	Item discriminability (d_a)
Experiment 1			
Self-Paced Offset	0.67 (0.16)	0.24 (0.17)	1.17 (0.79)
Self-Paced Onset	0.65 (0.18)	0.29 (0.24)	1.02 (0.80)
Fixed-Pace	0.66 (0.16)	0.33 (0.22)	0.88 (0.68)
Experiment 2			
Self-Paced Onset	0.69 (0.17)	0.34 (0.24)	0.95 (0.69)
Fixed-Pace	0.65 (0.18)	0.33 (0.19)	0.93 (0.61)
Experiment 3			
Self-Paced Onset	0.74 (0.16)	0.18 (0.18)	1.53 (0.92)
Fixed-Pace	0.74 (0.15)	0.19 (0.15)	1.55 (0.83)
Experiment 4			
Self-Paced Onset	0.57 (0.19)	0.29 (0.18)	0.76 (0.55)
Fixed-Pace	0.53 (0.18)	0.30 (0.18)	0.65 (0.52)

was ambiguous in the self-paced onset condition ($r(97) = .10$, $p = .332$, $BF_{10} = 0.36$) and in the fixed-pace condition ($r(94) = .11$, $p = .283$, $BF_{10} = 0.40$).

Experiment 2

In Experiment 1, self-pacing offsets of study material was found to benefit memory, but self-pacing of onsets was not. However, the fixed-pace condition may not have been an adequate control group. The study phase was longer in the self-paced onset condition ($M = 257.02$ s, $SD = 189.76$ s) than in the fixed-pace condition ($M = 229.12$ s, $SD = 145.87$ s, $t(99) = 3.22$, $p = .002$, $BF_{10} = 9.92$). This finding is reminiscent of the labor-in-vain effect, whereby increased time with study material does not lead to higher performance (Nelson & Leonesio, 1988). Although the words were exposed for the same amount of time across conditions, the uncontrolled timing between words is a potential confound. The purpose of Experiment 2 is to investigate the effects of self-pacing onsets using a control condition more appropriately tuned to the timing of gaps between words. Using a different yoking procedure also allows a modest generalization of the present findings. The fixed-pace condition in Experiment 2 is yoked to subjects in the self-paced onset condition, allowing for a cleaner comparison.

Participants

The sample size plan was to run subjects until a Bayes Factor of 3 (or 0.33) was reached in comparing the two conditions, or

until 200 subjects were collected. Optional stopping rules using Bayes Factors are acceptable because data peeking does not affect error rates (Lindley, 1957; Rouder, 2014). Using this rule, 81 participants were sampled using Amazon Mechanical Turk and compensated US$1 for their time. Three subjects were excluded because they missed trials during the study phase by leaving the experiment window. This occurred only in the fixed-rate condition where a response is not required to continue through the list. Thus, subjects who were dropped were re-collected and yoked to same self-paced subject. The final dataset consisted of 39 pairs of subjects (age: 18–58 years; gender: 43 female, 34 male, and one did not indicate; race: five Asian, 11 Black, 61 White, and one other)

Materials

Study materials were identical to Experiment 1. Yoked pairs received the same order of words for the study phase and recognition test.

Design

This experiment used a 2 (self-paced onset vs. fixed-rate) between-group design. Subjects in the fixed-rate condition were yoked to subjects in the self-paced onset condition.

Procedure

All subjects were instructed to study 80 words for a later test. The duration of each word presentation was fixed at 1 s. Those in the self-paced onset condition were able to control the onset of each word. The screen remained blank until the subject pressed the spacebar to view the next word. Thus, the timing
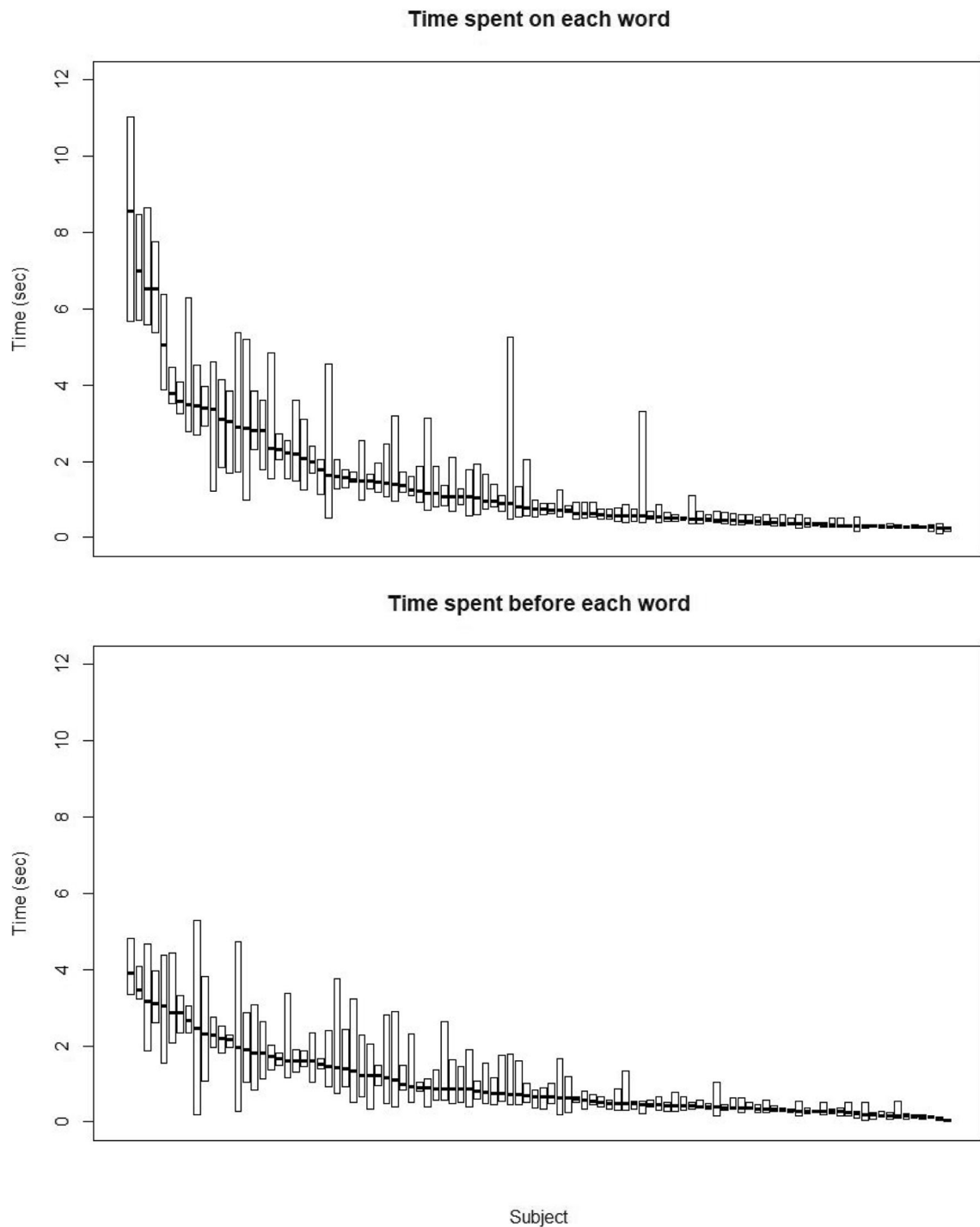
Fig. 2 Boxplots for item study time for each subject in the self-paced offset condition (top graph) and time spent before each word for subjects in the self-paced onset condition (bottom graph) in Experiment 1

of the word onset was under subject control, and the offset was fixed. Subjects in the fixed-rate condition did not have control over the onset of each word. Instead, the inter-stimulus interval time was determined by their yoked partner in the self-paced onset condition. The time between words in the fixed-rate condition was the average length of time between the 80 studied words of the self-

paced onset subject. The total time spent between words is thus equivalent across the pairs of subjects but distributed differently. A visualization of this yoking can be seen in Fig. 3. After studying the list of words, all subjects completed a 30-s distractor task in which they did simple arithmetic. Then all subjects were given a recognition test in the same format as Experiment 1.
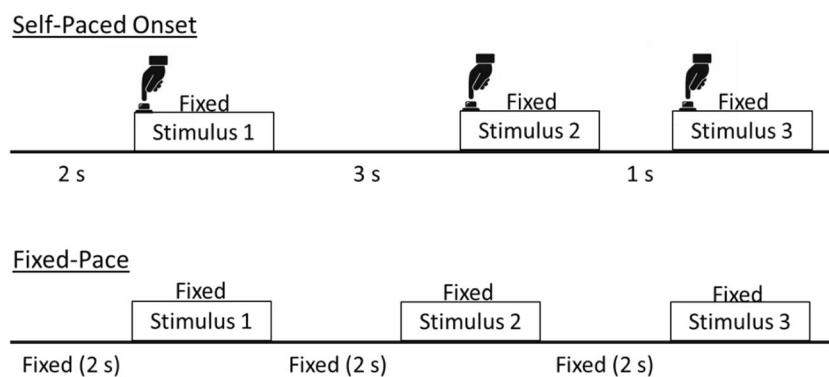
Self-Paced Onset

Fig. 3 An example of the design used in Experiment 2, Experiment 3, and Experiment 4 for each pair of subjects. Subjects in the self-paced onset condition determined when each stimulus would appear. In this example, the subject waited 2 s for the first stimulus, 3 s for the second stimulus, and 1 s for the third stimulus. On average, this participant spent 2 s between each word. Subjects in the fixed-paced condition were given 2 s between each word to equate overall study periods between the two conditions

Results

Condition analysis Hits and false alarms are reported in Table 1. Three pairs of subjects were removed from analysis because we were unable to calculate d_a: one in the fixed-pace condition and two in the self-paced onset condition. Self-paced onsets ($M = 0.95$, $SD = 0.69$) did not lead to higher discriminability than fixed-pacing ($M = 0.93$, $SD = 0.61$, $t(35) = 0.15$, $p = 0.879$, $BF_{10} = 0.18$). The evidence favored the null hypothesis of no difference between conditions, and led to cessation of data collection at $N = 81$.

Relationship between metacognitive control and memory The relationship between the time spent before and after a word (see Fig. 4) and probability of a hit was examined using a logistic regression for subjects in the self-paced onset condition. Average McFadden's R^2 value across subjects was again reliably, but minimally, larger than 0 for time spent before ($M = 0.02$, $SD = 0.04$, $t(38) = 3.25$, $p = .002$, $BF_{10} = 13.93$) and after the word ($M = 0.01$, $SD = 0.02$, $t(38) = 3.88$, $p < .001$, $BF_{10} = 69.97$).

Subjects who spent more time between words enjoyed an overall longer study period. Those who spent longer on average between words attained higher discriminability in the self-paced group ($r(36) = .41$, $p = .011$, $BF_{10} = 5.90$). This relationship was ambiguous for the fixed-pace group ($r(36) = 0.14$, $p = 0.389$, $BF_{10} = 0.50$).

Experiment 3

Experiment 2 did not show a benefit of self-paced onsets. Experiment 3 provides a replication of this test with a lab-based sample of undergraduates. The only procedural difference is that study times for Experiment 3 were increased to 4 s, making time spent with the
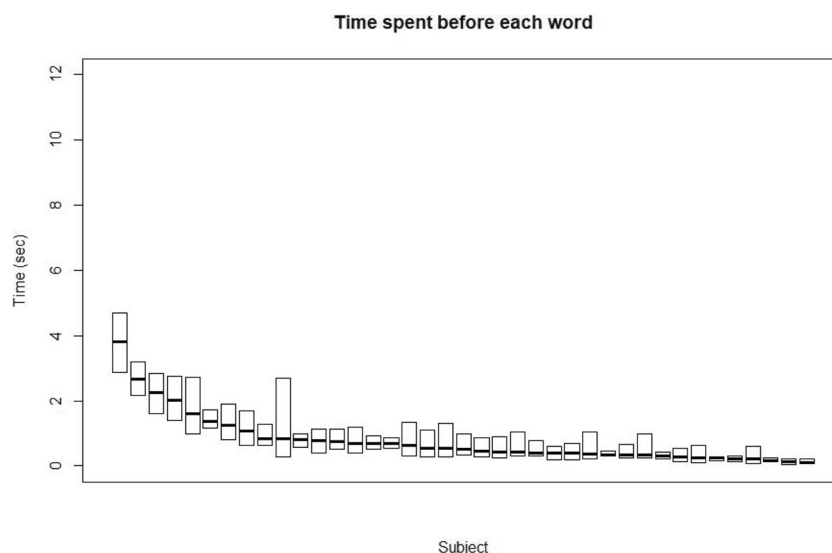
Time spent before each word

Fig. 4 Boxplots for time spent before each word for each subject in the self-paced onset condition in Experiment 2

material longer than both Experiment 1 (M = 1.87 s) and Experiment 2 (M = 1 s).

Participants

Because running subjects in the laboratory requires advance planning and scheduling of visits, we did not implement optional stopping but rather used the sample size logic employed in Experiment 1. Two hundred subjects (age: 18–24 years; gender: 116 female and 84 male; race: 72 Asian, 15 Black, 106 White, three Native American, and 13 other) from the University of Illinois participated in the experiment in exchange for course credit.

Materials

Study materials were the same as Experiment 1.

Design

This experiment used a 2 (self-paced onset vs. fixed-rate) between-group design. Subjects in the fixed-rate condition were yoked to subjects in the self-paced onset condition. All aspects of the design were the same as Experiment 2.

Procedure

Subjects were run on desktop computers in individual rooms. In each room, the first subject was assigned to the self-paced onset condition and the consecutive subject to the fixed-rate condition. The assignment of conditions continued to alternate, with the fixed-rate condition always following the self-paced onset condition. The procedure was similar to Experiment 2, except that words were presented for 4 s instead of 1 s.

Results

Condition analysis Hit and false alarm rates are reported in Table 1. A total of six pairs of subjects were excluded in analysis due to inability to calculate d_a from their data: two subjects in the self-paced onset and four subjects in the fixed-pace condition. Subject analysis revealed no difference in discriminability between the self-paced onset (M = 1.53, SD = 0.92) and the fixed-pace conditions (M = 1.55, SD = 0.83, t(93) = 0.22, p = .823, BF_{10} = 0.12). The evidence strongly favored the null hypothesis of no difference between conditions.

Relationship between metacognitive control and memory Data were only saved for average time spent between words, not variations for each word in the study phase. Thus, a relationship between time spent before and after a word and probability of a hit could not be conducted for this experiment. Subjects who had longer average timing between words in the

self-paced onset achieved higher discriminability (r(96) = .29, p = .004, BF_{10} = 12.28). This relationship was ambiguous for the fixed-pace condition (r(94) = .13, p = .224, BF_{10} = 0.47).

Experiment 4

Across the first three experiments, self-pacing the onset of stimuli did not provide an advantage to memory. It is possible that words, which can be verbally rehearsed, may not benefit from control of timing because their absence does not prohibit ongoing rehearsal. In Experiment 4, we selected study materials that make ongoing rehearsal much more difficult: faces. Evidence from previous research demonstrates that self-pacing offsets of face presentations does benefit memory (Tullis et al., 2014). A failure of control over onsets of faces would generalize the null findings from the prior experiments to a category of stimuli for which concerns about rehearsal are minimized.

Participants

A total of 219 participants were collected using Amazon Mechanical Turk and compensated US$1 for their time. Subjects were excluded if they left the task during the study phase (19 subjects). This only occurred in the fixed-pace condition and thus subjects were re-yoked. The stopping rule was the same employed in Experiment 2. The final dataset consisted of 200 participants (age: 19–86 years; gender: 112 female and 83 male; race: 17 Asian, 22 Black, 156 White, four other, and one didn't respond).

Materials

Subjects studied faces that ranged from 18–34 years of age, 80 of which were female and 80 of which were male. For each gender, 16 were Black and 64 were White. All faces were placed against a white background and the subject wore a black shirt. There were eight buffer items, four each at the beginning and end, to mitigate the effects of primacy and recency. Buffer items consisted of four male and four female White faces and were not included in the analysis. The face database used was created by Minear and Park (2004).

Design

This experiment used a 2 (self-paced onset vs. fixed-rate) between-group design. Subjects in the fixed-rate condition were yoked to subjects in the self-paced onset condition.

Procedure

The procedure was very similar to Experiment 2. Instead of words, subjects studied faces with a presentation rate of 1 s.

Results

Condition analysis One pair of subjects were removed due to inability to calculate d_a from a subject in the self-paced onset condition. Analysis revealed ambiguous results for the difference in discriminability for self-paced onset ($M = 0.76$, $SD = 0.55$) and the fixed-pace condition ($M = 0.65$, $SD = 0.52$, $t(98) = 1.64$, $p = 0.10$, $BF_{10} = 0.41$), a result that is not highly probative but that favors the null.

Relationship between metacognitive control and memory For subjects in the self-paced onset condition, the relationship between time spent before and after a studied face (see Fig. 5) and the probability of getting a hit was investigated. This was done subject-by-subject to control for individual differences in study time and memory. The average McFadden's R^2 for a logistic regression value for time before ($M = 0.02$, $SD = 0.03$, $t(99) = 5.40$, $p < .001$, $BF_{10} = 28,442.12$) and time after ($M = 0.02$, $SD = 0.03$, $t(99) = 6.25$, $p < .001$, $BF_{10} = 1.0 \times 10^6$) was reliably greater than 0, but only slightly.

When face stimuli were used, there was no correlation between the average time spent between faces and discriminability for either the self-paced onset ($r(97) = 0.08$, $p = .418$, $BF_{10} = 0.32$) or the fixed-pace condition ($r(97) = -0.08$, $p = .408$, $BF_{10} = 0.33$).

Discussion

The current set of experiments sought to investigate the ability of individuals to monitor attentional fluctuations and control the timing of study material to their advantage. Previous research has found a benefit for controlling duration of study material (Tullis & Benjamin, 2011). This benefit might be based on successful monitoring of the progression of learning,

over control over attention and perseveration through lapses thereof, or a combination of both. If individuals are able to monitor moments of focused attention, then control over the onsets of study events should improve memory. Experiment 1 replicated the finding that control over the duration of study material benefits memory, but failed to find a benefit for having control over the onset of study material. Using a different comparison group, Experiment 2 also failed to find a benefit in memory for subjects who had control over stimulus onset compared with those who did not. In Experiment 3, stimulus duration was increased and data were collected under controlled conditions in the lab. Still, control over stimulus onset did not lead to superior memory. Experiment 4 sought to extend this to a different set of stimuli (pictures of faces) that have previously been found to benefit from control of stimulus duration (Tullis et al., 2014). The findings favored the null, but provided inconclusive evidence for the role of self-pacing onset of studied faces. Together, these findings indicate strongly that individuals are unable to monitor attention fluctuations in a manner that materially impacts study behavior and improves memory.

To further examine the effect of self-pacing stimuli onset on memory, we conducted a mini-meta-analysis on the four experiments reported in this article. A visualization of the effect size comparing self-paced onset and fixed-pace conditions is shown in Figure 6. Overall, control over self-pacing onset of stimuli does not impact memory ($d=0.09$, 95% confidence interval (CI) = [-0.04, 0.23], $t(322) = 1.30$, $p = 0.196$, $BF_{10} = 0.14$). However, an item analysis yielded an intriguing result, shown in Fig. 7. When an item was in the self-paced onset condition, memory for that item was better than when it was in the fixed-pace condition ($d=0.17$, 95% CI = [0.11, 0.24], $t(639) = 5.70$, $p < .001$, $BF_{10} = 313,351$). The overall effect size is small, and it is difficult to discern if this effect
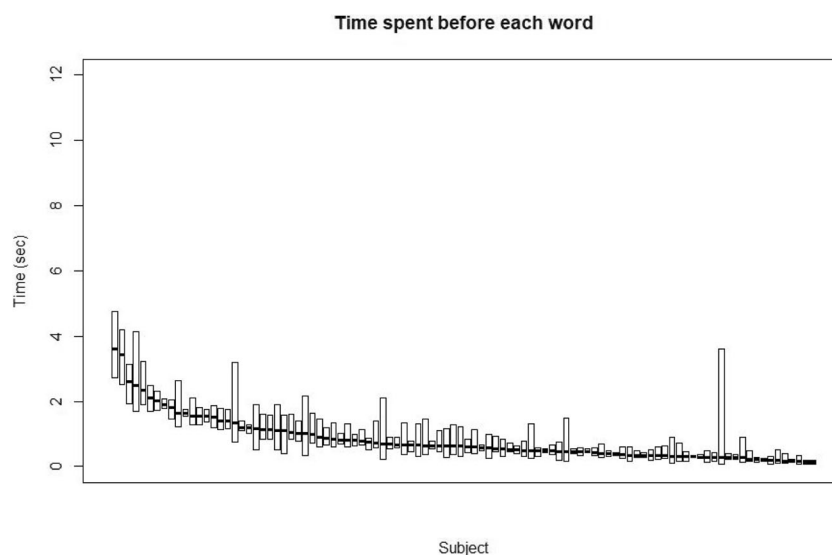

Fig. 5 Boxplots for time spent before each word for each subject in the self-paced onset condition in Experiment 4
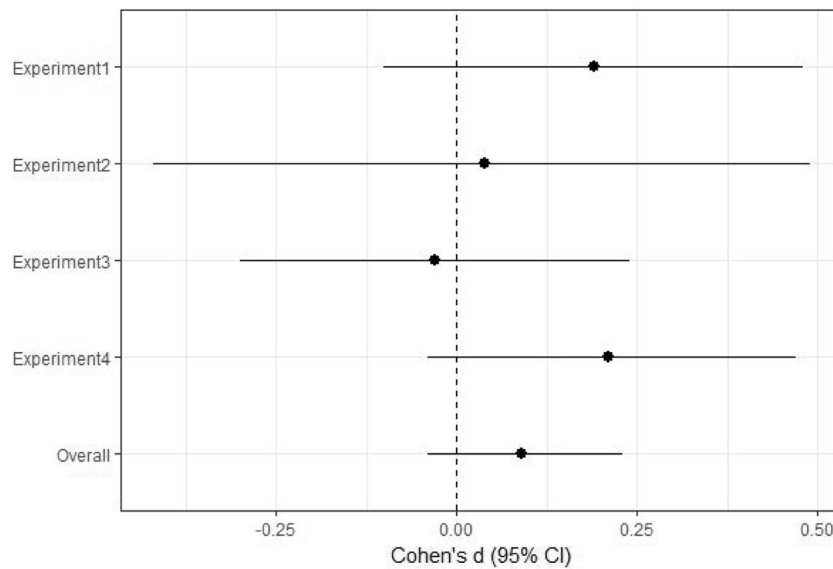
Fig. 6 Forest plot of effect sizes for the self-pacing onset and fixed-pace conditions across all subjects in the reported experiments. Error bars indicate 95% confidence intervals

alone demonstrates a benefit to self-pacing stimuli onset. Why this result should be apparent when examining items but not subjects is unclear. Taken together with the correlational results indicating a relationship between time spent around each study word and memory for that study word, it is possible that there are in fact advantages to control over onsets but that they are small and undetectable in paradigms like the one we have employed here.

One concern in the present work is that the timing of study phases in these experiments was open-ended and subjects were easily able to finish within 5–10 min. When stimuli are presented for brief periods of time, as they were in these experiments, there could be a lesser benefit for self-pacing of

study material. The duration of the study phase might not allow attention to fluctuate to a degree that would negatively impact memory. Longer study periods might be superior for addressing fluctuations in attention. It is also possible that the material used was not cognitively demanding enough to motivate a need to monitor attention. Clearly, more work across a variety of conditions and paradigms will be needed to fully understand the impact of self-pacing the onset of stimuli.

Control over the flow of information is a central component of the Atkinson and Shiffrin (1968) model of memory. Research on metacognitive control indicates that there are many ways in which we control that flow, and additionally demonstrates that we are mostly effective at doing so in such a
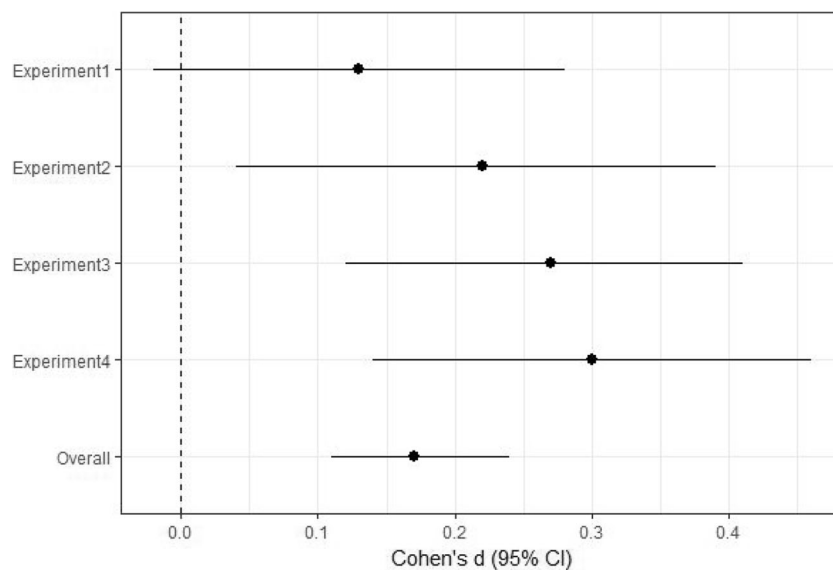

Fig. 7 Forest plot of effect sizes for item analysis in the self-pacing onset and fixed-pace conditions across all experiments. Error bars indicate 95% confidence intervals

way that meets our cognitive needs. Here we have sought evidence that humans can monitor fluctuations in attention and time encoding in such a way so as to mitigate negative consequences of those fluctuations. We failed to find evidence that control over the timing of onsets of information is actually beneficial. This is an interesting contrast to the consistent and reliable beneficial effects of control over offsets of information.

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