Attentional fluctuations and the temporal organization of memory

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Abstract

Event boundaries and temporal context shape the organization of episodic memories. We hypothesized that attentional fluctuations during encoding serve as “events” that shape temporal context representations and recall organization. Individuals encoded trial-unique objects during a modified sustained attention task. Memory was tested with free recall. Response time variability during the encoding tasks was used to characterize “in the zone” and "out of the zone" attentional states. We predicted that: 1) “in the zone”, vs. “out of the zone”, attentional states should be more conducive to maintaining temporal context representations that can cue temporally organized recall; and 2) temporally distant “in the zone” states may enable more recall “leaps” across intervening items. We replicated several important findings in the sustained attention and memory fields, including more online errors during “out of the zone” vs “in the zone” attentional states, and recall that was temporally structured. Yet, across four studies, we found no consistent evidence for either of our main hypotheses. Recall was robustly temporally organized, and there was no difference in recall organization for items encoded “in the zone” vs “out of the zone”. We conclude that temporal context serves as a strong scaffold for episodic memory, one that can support organized recall even for items encoded during relatively poor attentional states.

Key words: long-term memory, episodic memory, temporal context, event segmentation, sustained attention

Introduction

Episodic memories are temporally organized. Recall of a given event acts as a cue that can lead to recall of other events that were encoded close to it in time (Kahana, 1996; Howard & Kahana, 2002; Healey et al., 2019). This is thought to occur because events encoded close to one another in time have similar internal "temporal context" representations (Howard & Kahana, 2002). Although temporal contexts powerfully shape recall, the factors that drive how those temporal contexts form during encoding are relatively underexplored. A better understanding of those mechanisms can help individuals promote factors that create strong temporal contexts at encoding and thus enhance memory retrieval. Here, we test the hypothesis that natural fluctuations in attention during encoding contribute to temporal context representations.

The Temporal Context Model (TCM) was proposed to explain the temporal organization of episodic memory (Howard & Kahana, 2002). According to this model, at encoding, item representations are linked to a slowly changing but ever-present temporal context. When an item is recalled, the temporal context from encoding is also retrieved. Using the retrieved temporal context as a cue, other items studied with an overlapping temporal context can then be recalled (Howard & Kahana, 2002; Polyn & Kahana, 2008).

Free recall studies examining these effects typically use lag-Conditional Response Probability (lag-CRP) curves to characterize the temporal organization of recall (Kahana, 1996; Howard & Kahana, 2002; Healey et al., 2019; Palombo et al., 2019; Diamond & Levine, 2020). These lag-CRP curves exemplify two characteristic features of temporally structured recall: the temporal contiguity effect and the forward asymmetry bias. The temporal contiguity effect refers to the tendency for items encoded close in time to be recalled close in time (Howard & Kahana, 1999; Healey et al., 2019). The forward asymmetry bias refers to the greater probability of successively recalling items in a forward vs. backward direction. That is, for a given recalled item, subsequently recalled items are more likely to have been encoded after (rather than before) the first-recalled item (Polyn & Kahana, 2008; Polyn et al., 2009). This forward asymmetry bias is thought to arise because a given item becomes part of the temporal context for succeeding items, and can thus serve as a memory cue.

This research has largely proposed that temporal contexts are ever-present and slowly drift during an encoding experience, as newly encountered items and thoughts are incorporated into the temporal context representation. Whether certain cognitive and environmental factors can affect the drift of temporal context is an important question, because such factors may promote (or hinder) memory retrieval (DuBrow et al., 2017). Recent research has shown that event segmentation can serve as one such factor that impacts the temporal organization of memory. Event segmentation theory hypothesizes that our ongoing experience is parsed into "segments" with the transition between segments acting as an event boundary (Zacks et al., 2007; Clewett & Davachi, 2017; Heusser et al., 2018). Memory retrieval is strongly shaped by such event boundaries: the order of events is remembered better, and events are more likely to be remembered as being closer together, if they were experienced within the same event segment vs. different event segments (DuBrow & Davachi, 2013, 2016; Heusser et al., 2018; also see Ezzyat & Davachi, 2010; DuBrow & Davachi, 2014; Ezzyat & Davachi, 2014).

We propose that similar to event boundaries, natural fluctuations in attention may contribute to how temporal contexts form during encoding. Fluctuations in attention are inherent aspects of human nature (Killingsworth & Gilbert, 2010). People tend to experience times when attention peaks, leading to intense focus on the task at hand, while at other times, attention wanes and focus is broken by intrusive thoughts, distractions, or fatigue (Smallwood et al., 2008). Despite the ubiquity of such attentional fluctuations, past work examining how attention affects memory has typically focused on experimental manipulations of attention rather than spontaneous fluctuations. Such work has shown that experimental manipulations (such as directing participants' external attention towards a specific object, color, or spatial location) improve later memory for the attended event, but hurt memory for unattended events (Anderson et al., 1998; Craik et al., 1996, 2018; Naveh-Benjamin et al., 1998; Troyer et al., 1999; Troyer & Craik, 2000; Yi & Chun, 2005; Chun & Turk-Browne, 2007; Chun et al., 2010; Uncapher et al., 2011; Turk-Browne et al., 2013; LaRocque et al., 2015; see Aly & Turk-Browne, 2017).

A different body of work, on mind-wandering, has examined natural fluctuations of attention (Smallwood & Schooler, 2006; Christoff et al., 2016; also see Smallwood & Schooler, 2015). In these studies, participants are asked, with intermittent probes, to self-report whether they were "on task" or "mind-wandering" (e.g., Metcalfe & Xu, 2016; Xu & Metcalfe, 2016; Xu et al., 2018; Garlitch &

Wahlheim, 2020) or asked to describe their thoughts at the time of the probe (Smallwood et al., 2003). These fluctuations in attention impact subsequent memory, such that mind wandering is related to worse memory (Smallwood et al., 2003; Risko et al., 2012; Garlitch & Wahlheim, 2020; Martarelli & Ovalle-Fresa, 2021). However, these studies are limited in that they only capture participants' attentional state at a few discrete time points and cannot precisely characterize the temporal dynamics of intrinsic fluctuations in attention. Furthermore, such studies have not determined how mind wandering may affect the temporal structure of memory.

Sustained attention research offers a way to measure moment-by-moment fluctuations in attention (Robertson et al., 1997; Sarter et al., 2001; Smallwood & Schooler, 2006; Rosenberg et al., 2011; Esterman et al., 2013; deBettencourt et al., 2015; Rosenberg et al., 2017; deBettencourt et al., 2018; Fortenbaugh et al., 2018; Esterman & Rothlein, 2019; Elshiekh & Rajah, 2021). One type of task, the gradual onset continuous performance task (gradCPT), uses reaction time (RT) variability to index moment-by-moment fluctuations: trials with greater RT variability constitute "out of the zone" attentional states, while trials with lower RT variability reflect "in the zone" attentional states. Online task performance differs based on these attentional states: participants make more errors in the task during an "out of the zone" attentional state (Rosenberg et al., 2011; Esterman et al., 2013; Rosenberg et al., 2017). These studies, however, do not relate attentional fluctuations during the task to subsequent memory (see Madore et al., 2020 for a trait-level analysis). A related approach to characterizing attentional fluctuations based on RT showed that being in a good attentional state results in better recognition memory later on (deBettencourt et al., 2018), but that study did not examine the temporal organization of memory. Building on these studies, in the current work, we use response time variability to characterize "in the zone" and "out of the zone" attentional states. We employed a modified version of the gradCPT, in which participants encoded trial-unique objects in the study phase (i.e., the sustained attention phase) and were later asked to verbally recall as many objects as they could in any order they chose. This allowed us to examine how moment-by-moment fluctuations in attention during encoding influence the temporal structure of recall.

We tested two main hypotheses. First, that recall will be more temporally structured when items are encoded "in the zone" vs. "out of the zone". This may occur because being focused on the task at hand leads to a consistent mental state, which can serve to bind and maintain a temporal context representation. Such focused attention may also facilitate linking attended events in the environment to these internal temporal contexts. Conversely, the reduction of task-focused thought in a “bad” attentional state may result in switches between internally and externally focused thought that disrupt a consistent temporal context representation, and/or hurt the ability to link items in the environment to internal temporal contexts. If this is the case, then the hallmarks of temporally organized memory — temporal contiguity and forward asymmetry — may be enhanced for items encoded “in the zone” vs “out of the zone”.

Our second hypothesis is motivated by the finding that recall can “leap” between cognitively similar but temporally distant events (Chan et al., 2017). This may occur because one’s thoughts become integrated into temporal context representations: similar thoughts trigger similar temporal context representations, and in that way facilitate successive recall of items associated with cognitively similar contexts. We hypothesize that “in the zone” states, even if separated in time, constitute cognitively similar events: they consist of a focused mindset and the particular strategies that a person brings to mind to succeed in the ongoing task. On the other hand, we hypothesize that temporally distant “out of the zone” states are cognitively *dissimilar* events: every time an individual is unfocused, they may be unfocused in a different way, as their attention switches between the task and other ongoing, fluctuating thoughts. If this is the case, then recall may be more likely to “leap” between different “in the zone states” than different “out of the zone” states, bypassing items that were encoded in the other attentional state.

In sum, we aim to examine the behavioral effects of spontaneous attentional fluctuations on the temporal organization of recall. We characterize attentional fluctuations based on response time variability during an encoding task, classifying trials into relatively good “in the zone” and relatively worse “out of the zone” attentional states. To do that, we use a modified version of the gradCPT, introducing changes that make the task more suitable for examining subsequent memory. This includes using trial-unique nameable objects, slower presentation durations, and fewer trials (see **Methods** for more details). Participants’ memory for the trial-unique objects was then tested with free recall. Lag-CRP curves, and analyses of recall based on different “in the zone” and “out of the zone” event segments, allowed us to test whether and how attentional fluctuations shape the temporal organization of memory.

Study 1

Methods

Design

Participants

We conducted an *a priori* power analysis using G* Power (Faul et al., 2007, 2009). Due to the lack of prior work involving spontaneous attentional fluctuations and temporal organization of recall, we calculated the number of participants required to both a) replicate typical properties of the temporal organization of recall, including main effects of, and the interaction between, absolute lags and direction (Kahana et al., 2002; Spillers & Unsworth, 2011; Palombo et al., 2019; Diamond & Levine, 2020); and b) observe interactions between lag-CRP properties (absolute lag or direction) and other independent variables (Palombo et al., 2019; Diamond & Levine, 2020); this was done to approximate interactions between lag-CRP properties and attentional state). For 80% power and an alpha of 0.05 in a within-participant design, we determined that the minimum required sample size was 50 participants. We opted to exceed that to counteract effect size overestimation resulting from publication bias (Brand et al., 2008; Bakker et al., 2012). We therefore report data from 65 participants (M_{age} = 25.17 ± 6.67 years, $M_{education}$ = 14.78 ± 2.23 years). 33 identified as female, 28 as male, 3 as non-binary, and 1 did not specify. In terms of race, 33 participants identified as White, 16 as Asian, 8 as Black or African American, 5 as bi-racial, 1 as American Indian/Alaskan Native, 1 as Middle Eastern, and 1 as Other. In terms of ethnicity, 59 participants identified as not Hispanic or Latino, and 6 as Hispanic or Latino. We do not report data from an additional 15 participants, who were excluded due to image loading errors (N = 6), low response rate during the encoding task (<80%, N = 2), outlier response accuracy during the encoding task (>3 SD from the group mean; N = 3), recall recording issues (N = 3), and incomplete data due to technical problems (N = 1).

Of the final sample, 22 participants were recruited from the Columbia University participant pool. They completed the study in the lab and were compensated with course credit. Because of the COVID-19 pandemic and the related shutdown, the remaining participants (N = 43) were recruited through Prolific (www.prolific.co). They participated in an online version of the same experiment hosted on the Gorilla platform (www.gorilla.sc; Anwyl-Irvine et al., 2020). Participants were 18 to 40 years of age, fluent in English, and resided in the US (inclusion criteria were specified in Prolific prior to recruitment). Both groups of participants provided informed consent in accordance with the Columbia University Institutional Review Board. No statistically significant differences were observed between the in-person and Prolific samples in any measure of interest (all *p*s > .089 for all main effects and interactions involving the 'sample' variable); thus, all data analyses include the combined sample. Nevertheless, for completeness, we report statistics to compare the two groups for effects of interest.

Stimuli

We chose 191 images of objects from pre-curated object databases such as SOLID (Frank et al., 2020), stimuli from the Mnemonic Similarity Task (Yassa et al., 2011; https://faculty.sites.uci.edu/starklab/mnemonic-similarity-task-mst/), Interaction Envelope (Bainbridge & Oliva, 2015a, 2015b; http://www.wilmabainbridge.com/datasets.html), and the Bank of Standardized Stimuli (Brodeur et al., 2014; https://sites.google.com/site/bosstimuli/). Color images were converted to grayscale.

These images were assigned to 5 study blocks using the OptSeg tool (Siegelman, 2019; https://github.com/msieg/OptSeg_Reproducible), which pseudo-randomizes the stimuli into lists while controlling for semantic similarity between constituent words. Semantic similarity between two items was measured as the cosine distance between the 300-dimensional GloVe vectors of the object names (Siegelman, 2019). Given a pool of words, the algorithm constructs lists so that items within a list are as semantically dissimilar as they can be. This allowed us to focus on temporal organization within lists that minimized opportunities for semantic organization given the stimuli available (Manning & Kahana, 2012). All 191 images were provided to the algorithm to have some leeway in assigning semantically matched and optimized lists. We created 5 lists of 30 images each using this procedure. The 5 stimulus lists were then randomized to 5 study blocks with within-block randomization of image order. The remaining 41 images were used for the practice block before the main task.

Procedure

The experiment was composed of 5 blocks, each of which included a study phase, a distractor phase, and a recall phase (**Figure 1**).

In each of the 5 study phases, participants viewed a series of 30 trial-unique images of common objects. The objects transitioned from one into another over 5 seconds. Each object remained on the screen for 1 second before the start of the next transition. Every 0.5 seconds the first object's opacity decreased by 10% while the succeeding object’s opacity increased by 10%. This slow transition ensures that there is no capture of attention by abrupt image onsets, and helps induce more fluctuations of attention (Esterman et al., 2013). For each presented image, participants were asked to judge if the depicted object was “smaller or larger than a shoebox” using one of two keys. These two keys were counterbalanced across participants. Participants could respond at any time once the object had started fading in (**Figure 1**).

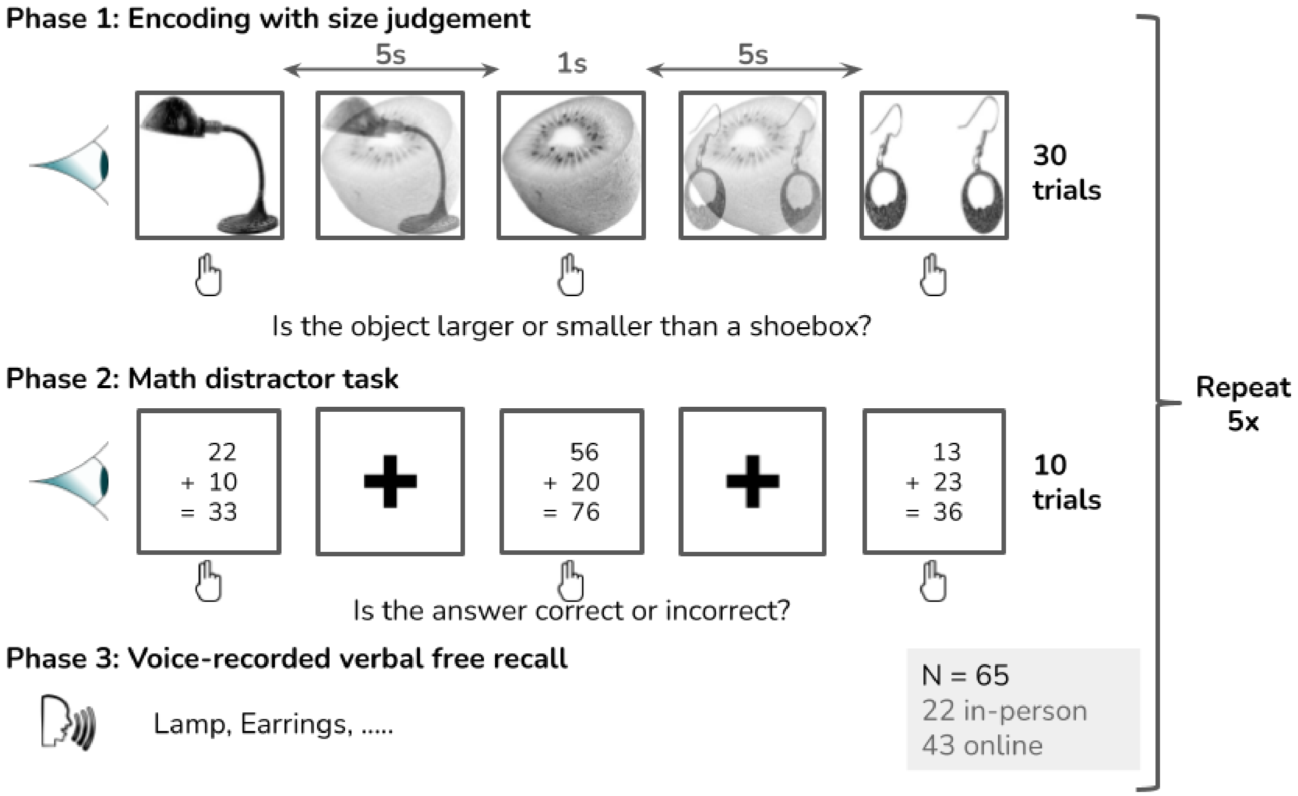

Figure 1. Schematic of the experimental design for Study 1. Participants were presented with a series of grayscale objects in the study phase. They were asked to judge if each object is smaller or larger than a shoebox. Object images gradually transitioned from one into another. Following a distractor math phase, participants were asked to verbally recall objects from the study phase, in any order that they choose. This 3-phase sequence was repeated in 5 blocks, with 30 images encoded each time. Study 2 was similar except that there were 3 blocks of 80 items each and the task was to press a button for non-food items and withhold a response for food items. Study 3 had 3 blocks of 60 items each and the task was to press a button for color images and withhold a response for grayscale images. In Study 3, there were no gradual transitions between items; each image was shown for 3s with a 2s inter-item interval. Study 4 was similar to Study 2, except that there were 2 blocks of 120 images each, and the trial duration was reduced from 6s to 4s.

A distractor phase followed each study phase, to introduce a delay between memory encoding and subsequent recall. Participants were presented with a sequence of 2-digit additions and subtractions. One solution to each question was provided and participants had to judge if the solution was correct or incorrect using one of two keys. Each trial began with a fixation cross presented for 2 seconds, followed by the arithmetic question for 5 seconds. 10 arithmetic questions were presented in each phase.

Memory recall immediately followed this distractor task. During each recall phase, participants were asked to verbally recall, in any order, as many objects as they could from the preceding study phase. This phase was recorded using a microphone. There was a time limit of 2-2.5 minutes (see below), and a countdown timer was displayed to indicate the time remaining.

Before beginning the experimental blocks, participants performed a practice block. The practice block was identical to the experimental blocks except that only 15 objects were presented in the study phase.

Both versions of the task (in-person and online) were similar except for two minor modifications. The verbal recording for the in-person version was 2.5 minutes long for each recall portion; for the online version, it was 2 minutes long (the maximum allowed on Gorilla). Because participants rarely used the entire 2.5 minutes for recall in the in-person version, this was a minor change that had no measured impact on performance (overall recall was not significantly different between the in-person and online groups ($t_{49.25}$ = 1.76, p = 0.09, Cohen's ds = 0.46, 95% CI [-1.35, 20.35]) nor was recall organization different between the groups, all *p*s > .1 for interactions involving sample [online vs in-person] in lag-CRP and event transition analyses discussed below). Additionally, the practice items for the in-person version were chosen from the leftover images after the Optseg assignment, and different participants were shown a different set of images. However, for the online version all participants saw the same 15 images in a randomized order.

Analyses

Defining attentional states at encoding

Attentional states were defined using response times (RTs) for the judgements made during the study phase. A variance time course (VTC) analysis was performed on the RT data using the procedure in Esterman et al., 2013. This procedure enables the identification of two attentional states ("in the zone" and "out of the zone") based on the variability of RT. Each correct trial was assigned a value corresponding to the absolute deviation of the trial RT from the mean within-block RT. Trials without a response and trials with an incorrect response were not included in this step. Next, this value was linearly interpolated (from the neighboring two trials) for trials without a response and trials with an incorrect response. If only one trial was available for interpolation (i.e., because trials at the beginning or end of a block do not have two surrounding trials), then RT was not interpolated and such trials were not assigned an attentional state. Then, a Gaussian smoothing kernel was applied to integrate information from the 4 surrounding trials. Finally, a median split was performed on these smoothed variance time course values, dividing the trials into those with lower RT variability (i.e., RTs closer to the mean; “in the zone” states) and higher RT variability (i.e., RTs farther away from the mean; “out of the zone” states).

Errors at encoding

In prior studies, “out of the zone” (vs. “in the zone”) attentional states were associated with more errors in sustained attention tasks (Rosenberg et al., 2011; Esterman et al., 2013). To determine if we could replicate those findings, we examined whether there was a difference between the two attentional states in the number of errors made during the encoding task, which was designed to be similar to the sustained attention tasks used in prior studies. First, objects depicted by each image were classified as being either larger than a shoebox (e.g., helicopter, treadmill), smaller than a shoebox (e.g., onion, key), or ambiguous (e.g., cowboy hat, soda bottle). Next, errors were calculated as the number of incorrect responses made to the objects that were unambiguously classified (i.e., responses to ambiguous objects were never counted as incorrect). (Note that accuracy was therefore the percentage of presented items with a correct response, for which responses to ambiguous objects were always counted as correct). Finally, we examined whether the number of errors made during “out of the zone” attentional states was greater than the number of errors made during “in the zone” states. Group-level analyses were conducted with a paired-samples t-test.

Recall performance

We calculated recall performance as the total number of correctly recalled items across all blocks. To examine whether recall performance differed by attentional state, we calculated recall performance for each attentional state (“in the zone” or “out of the zone”) as the total number of correctly recalled items that were encoded in that particular attentional state. Note that because these attentional states are defined by a median split of the encoding RTs, the same number of items are encoded in each state. Group-level analyses were conducted with a paired-samples t-test.

Temporal organization of recall

We measured the temporal organization of recall using lag-Conditional Response Probability (lag-CRP) curves (Kahana, 1996). The lag-CRP curve measures the probability of recalling two items successively as a function of their relative position, or lag, at encoding. To plot these curves, we first obtain the encoding lag between all pairs of successively recalled items, where the lag is the difference between their serial positions at encoding. The lag can be positive or negative, depending on whether the subsequent item recalled was encoded after (positive lag) or before (negative lag) the preceding item. The observed number of recall transitions at each lag is then divided by the number of opportunities to make a recall transition at that lag, e.g., all the times a participant could have recalled an item at a +1 lag, regardless of whether or not they did (Kahana, 1996). This yields the probabilities plotted in the lag-CRP curve, i.e., actual transitions divided by possible transitions at each lag. Repetitions and intrusions are masked from this analysis: transitions to and from repetitions (recalled items that had also been recalled earlier) and intrusions (items recalled from a prior study list) are excluded (Kahana, 1996). The conditional response probability for each lag was calculated at the level of each block and then averaged across blocks, resulting in one CRP value at each lag for each participant.

Lag-CRP curves depict two characteristic features of the temporal organization of recall: forward asymmetry and temporal contiguity. Forward asymmetry refers to the greater likelihood of recalling in the forward vs. backward direction (i.e., greater conditional probability of recall for positive lags vs. negative lags, respectively). Temporal contiguity refers to the greater probability of recalling items together if they were encoded closer together in time (Kahana, 1996; Healey et al., 2019). This is seen as a peak in the lag-CRP curves: recall is more likely for items at ±1 lag, and recall probability decreases gradually with increasing lags.

To test for typical properties of lag-CRP curves, i.e., the temporal contiguity effect and forward asymmetry bias, we performed a two-way repeated-measures ANOVA on the lag-CRP measures with absolute lag (1 to 29) and direction (forward vs. backward) as factors (Palombo et al., 2019; Diamond & Levine, 2020). We tested the sphericity assumption using Mauchly's test of sphericity and applied the Greenhouse-Geisser correction when this assumption was not satisfied.

Our primary hypothesis was that "in the zone", vs. "out of the zone", attentional states are more conducive to maintaining a temporal context representation. If so, there should be a difference in the temporal organization of recall between the attentional states: temporal contiguity and/or forward asymmetry should be stronger for “in the zone” vs. “out of the zone” attentional states. To test this, we constructed separate lag-CRP curves for the two attentional states. First, individual pairs of successively recalled items were labelled as being in the same state (i.e., both encoded during an “in the zone” or “out of the zone” attentional state) or being a transition pair from one state to another. To calculate the lag-CRP curves separately for each state, we only considered pairs that were in the same state; transition pairs were excluded from analysis (see **Recall Transitions by Event Segment** for consideration of state transitions). As before, the actual transitions were calculated as the lag between the two successively recalled items based on their encoding position. These actual transitions were divided by the number of times a transition of a given lag could have possibly occurred irrespective of attentional states (i.e., all possible transitions). The conditional response probability for each lag was calculated within-block for each attentional state. These values were then averaged across blocks, resulting in one CRP value at each lag for each attentional state for each participant. This procedure is therefore identical to the main lag-CRP analysis, except that actual recall transitions were calculated separately for pairs of successively recalled items that were both encoded “in the zone” and pairs of successively recalled items that were both encoded “out of the zone”.

To test for a statistical difference in the temporal organization of recall between the two attentional states, we performed a three-way repeated-measures ANOVA with attentional state (“in the zone” vs. “out of the zone”), absolute lag (1 to 29), and direction (forward vs. backward) as factors with Greenhouse-Geisser correction applied when the assumption of sphericity was violated. Because there is a possibility that including all lags could mask differences in forward asymmetry — which is typically most prominent at nearby lags — we conducted an additional analysis. We examined whether there was a difference between the two attentional states in forward asymmetry at the closest lags of ± 1, by performing a two-way repeated-measures ANOVA with lag (+1 vs. -1) and attentional state (“in the zone” vs. “out of the zone”) as factors (Diamond & Levine, 2020).

Recall Transitions by Event Segment

The above temporal organization analyses do not differentiate between qualitatively different types of transitions that are possible within each attentional state. In particular, because individuals fluctuate between “in the zone” and “out of the zone” periods during encoding, each instance of an attentional state can be considered its own “event segment” (**Figure 2**). These different segments are ignored in the lag-CRP analysis above, which simply considers each attentional state as a whole. Furthermore, our “in the zone” and “out of the zone” lag-CRPs ignored recall transitions *between* “in the zone” and “out of the zone” states. Yet, considering these types of transitions is important: research on event boundaries has shown that successive recall of adjacently encoded items is more likely when those items are encoded in the same vs. different events (Ezzyat & Davachi, 2010; DuBrow & Davachi, 2013, 2016; Heusser et al., 2018; also see DuBrow & Davachi, 2014; Ezzyat & Davachi, 2014) and recall may “leap” between cognitively similar but temporally distant events (Chan et al., 2017). We therefore designed an analysis to test whether fluctuations between attentional states can act as event boundaries that reproduce the phenomena observed in research on events.

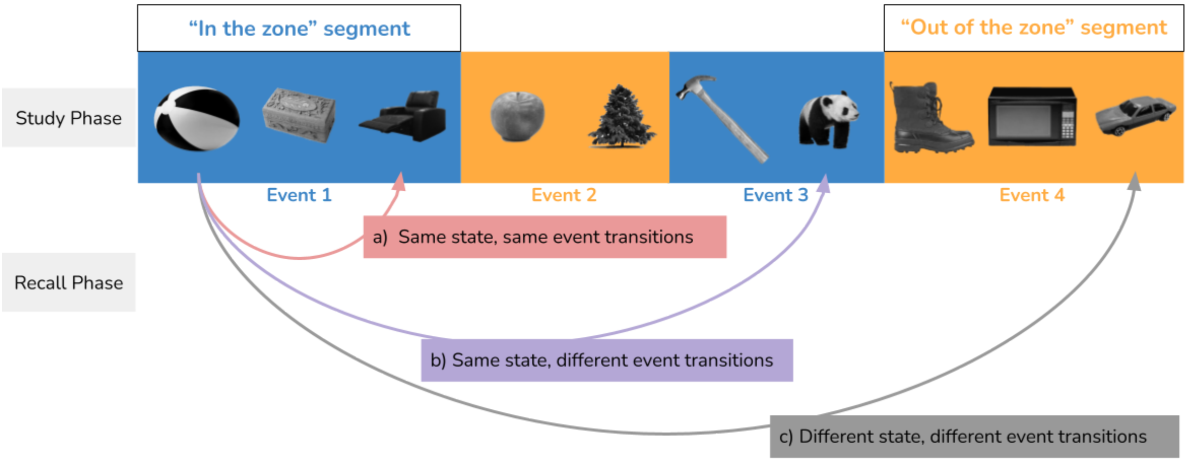

Figure 2. Types of transitions at recall. Individuals fluctuate between “in the zone” (blue) and “out of the zone” (orange) attentional states during encoding. Each instance of each attentional state can be considered its own “event segment”. For example, the ball and the recliner are encoded in the same attentional state and the same event segment within that state (“same state, same event”), whereas the ball and the panda are encoded in the same attentional state but during different event segments (“same state, different event”). The ball and the car are encoded in different attentional states and therefore, by necessity, different event segments as well (“different state, different event”). In the recall phase, given the recall of one object, the transition to the second object can be therefore categorized as one of three types: 1) same state, same event; 2) same state, different event; and 3) different state, different event.

This analysis allowed us to test whether 1) recall transitions within an “event segment” are more likely for “in the zone” vs. “out of the zone” attentional states; and 2) whether recall for “in the zone” states is more likely to “leap” from one event segment to another, bypassing items that were encoded in an “out of the zone” attentional state (Chan et al., 2017; also see Heusser et al., 2018). To examine these hypotheses, we first calculated the number of transitions made during recall for each type of transition noted in **Figure 2** (same state, same event; same state, different event; different state, different event), separately for each attentional state ("in the zone" vs. "out of the zone"). We normalized the number of transitions in each bin by the number of opportunities to transition to another item that falls within the same type of transition for that attentional state. The resulting value is therefore the conditional probability of each transition type. For example, we normalized the number of "same state, same event" transitions for "in the zone" items by the number of opportunities to make "same state, same event" transitions for items encoded "in the zone". These conditional probabilities were calculated separately for each block, and then averaged across the blocks for each participant. We then performed a two-way repeated-measures ANOVA with the type of transition (3 levels) and attentional state (2 levels) as factors.

Results

Defining attentional states at encoding

In the encoding task, participants viewed images of objects and judged each as being larger or smaller than a shoebox. Overall, mean response time (RT; defined from the onset of an image fading in; see **Methods** and **Figure 1**) was 3.67s (SD = 1.4s). Median RT was 3.94s.

We defined attentional states by performing a variance time course (VTC) analysis on the encoding phase RTs (Esterman et al., 2013). This procedure identifies two attentional states: the good "in the zone" attentional state (trials with lower RT variability, i.e., RTs closer to the mean) and the worse "out of the zone" attentional state (trials with higher RT variability, i.e., RTs farther away from the mean). **Figure 3A** shows the VTC analysis for one sample participant.

The mean length of a continuous "in the zone" segment was 3.50 trials (SD = 0.43) and the mean length of a continuous "out of the zone" segment was 3.54 trials (SD = 0.50; Note that a trial was 6 seconds long). The mean length of a segment did not differ between the two attentional states (t_{64} = 0.94, p = 0.35, Cohen's dz = 0.12 95% CI [-0.04, 0.11]). The mean number of fluctuations within a block (i.e., the number of times participants transitioned from one state to another) was 7.34 (SD = 0.99). The number of trials within a continuous segment ranged from 1 to 14, for both "in the zone" and "out of the zone" states, across all blocks and participants.

These attentional states were used to examine accuracy on the encoding task and subsequent recall performance, described below.

More encoding errors during "out of the zone" attentional states

Participants generally performed very well on the encoding task ("Is this object smaller or larger than a shoebox?"). The mean percentage of trials participants responded to was 93.36% (SD = 5.28%, Median = 94.00%). Mean accuracy (as defined in **Methods**) was 88.14% (SD = 7.38%, Median = 90.78%).

We next examined errors in the encoding task as a function of attentional state. Prior studies have shown that "out of the zone", vs. "in the zone", attentional states are associated with more errors (Rosenberg et al., 2011; Esterman et al., 2013). We replicated these findings in the current study. A paired samples t-test revealed that participants made significantly more errors in the encoding task during an "out of the zone" attentional state (mean ± SD: 12.12 ± 8.10) compared to an "in the zone" attentional state (8.57 ± 5.38; t_{64} = 5.49, $p < 0.0001$, Cohen's dz = 0.69, 95% CI [2.26, 4.85], **Figure 3B**). Thus, the VTC analysis is successful in identifying fluctuations between better and worse attentional states, even in our modified procedure.

Overall recall does not differ between the two attentional states

We next turned to examining memory for the objects viewed during the encoding task. Mean recall, calculated as the total number of items correctly recalled across all blocks, was 50.65 (SD = 22.06); mean recall within a block was 10.21 (SD = 4.37).

We then separately examined recall performance based on whether items were encoded "in the zone" or "out of the zone". We hypothesized that recall performance would be superior for "in the zone" attentional states. However, we did not find a significant difference in recall performance between "in the zone" (Mean ± SD 24.72 ± 10.9) and "out of the zone" (24.14 ± 11.52) attentional states (t_{64} = 0.80, $p = 0.43$, Cohen's dz = 0.10, 95% CI [-0.88, 2.05], **Figure 3C**). Thus, even though these attentional states differed in *online* task performance, subsequent recall was surprisingly not different.

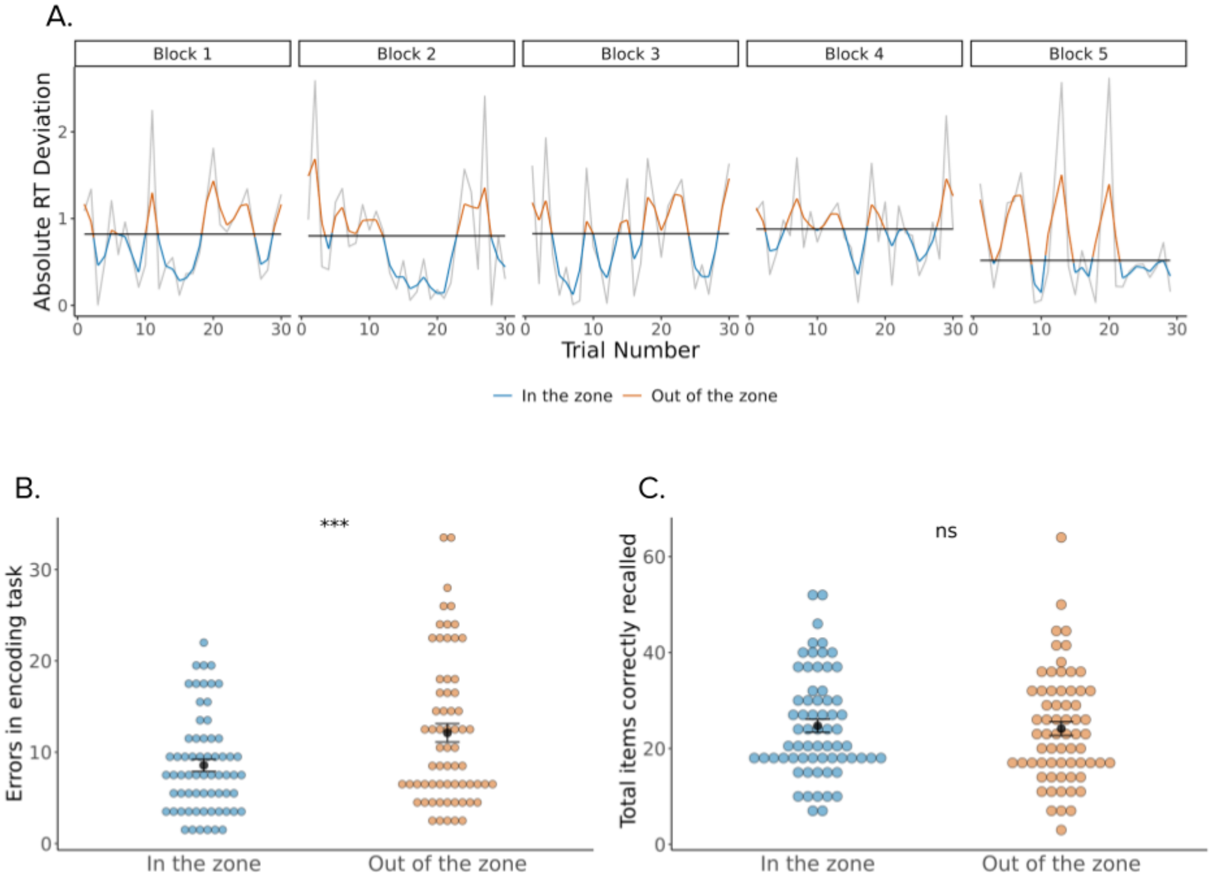

Figure 3. Encoding task performance and recall performance in Study 1. Encoding errors differ between attentional states but recall performance does not. **A.** Variance Time Course (VTC) analysis for a sample participant. Two attentional states were identified by median split of smoothed, absolute RT deviations from the mean: 1) an "in the zone" attentional state (blue) with less RT variability, i.e., RTs closer to the mean and, 2) an "out of the zone" attentional state (orange) with greater RT variability, i.e., RTs farther away from the mean. Horizontal black lines indicate the median absolute RT deviation per block. Gray curves indicate raw (unsmoothed) RT deviation per block. **B.** Individual points show the number of encoding judgement errors made by each participant during "in the zone" and "out of the zone" attentional states. Participants made significantly more encoding errors during the "out of the zone" state. **C.** Individual points show the total number of items correctly recalled by each participant as a function of whether items were encoded "in the zone" or "out of the zone". There was no difference in recall performance between the two states. Black points in panels B & C indicate the mean of the measure with standard error bars. *** p < .0001. ns = not statistically significant.

No differences in temporal contiguity or forward asymmetry between the two attentional states

Although overall recall was not different between "in the zone" and "out of the zone" attentional states, it is possible that there may be more subtle differences in *how* information is recalled. We therefore turned to our main analyses of interest, which explore the temporal organization of recall. We hypothesized that “in the zone” attentional states are more conducive to maintaining temporal context representations that facilitate temporally organized recall. We therefore used lag-CRP curves to test whether temporal contiguity and/or forward asymmetry were stronger for “in the zone” vs. “out of the zone” states.

Figure 4A shows the overall lag-CRP curve, across participants and blocks, regardless of attentional state at encoding. This curve depicts the probability of recalling two items successively based on their relative position, or lag, at encoding. To test for typical properties of lag-CRP curves, we conducted a two-way repeated-measures ANOVA on the lag-CRP measures (i.e., lag-conditional recall) with absolute lag (1 to 29) and direction (forward vs. backward) as factors. The Greenhouse-Geisser correction was applied to the absolute lag effects, which violated the assumption of sphericity. We found a significant main effect of absolute lag ($F_{12.6,\ 806.4}$= 11.05, $p < 0.0001$, η_p^2 = 0.15): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. There was no main effect of direction ($F_{1,64}$ = 0.28, p = 0.60, η_p^2 = 0.004), nor an interaction between absolute lag and direction ($F_{14.84\ 949.76}$= 1.48, p = 0.11, η_p^2 = 0.02). Thus, while we replicated the temporal contiguity effect reported in the literature, we did not replicate the forward asymmetry bias in the lag-CRP curves. However, a paired-samples t-test on the CRP values for +1 and -1 lags revealed that recall transitions were marginally more likely in the forward (+1) vs. backward (-1) direction (t_{64} = 1.91, p = 0.06, Cohen’s dz = 0.24, 95% CI [-0.001, 0.058]). Thus, a weak forward asymmetry bias was present in these close transitions.

We next tested our primary hypothesis that a good (vs. bad) attentional state at encoding would be related to better temporal organization of subsequent recall. To examine this, we constructed separate lag-CRP curves for “in the zone” vs. “out of the zone” attentional states based on successive recall of items encoded in the same state (**Figure 4B**). We conducted a three-way repeated-measures ANOVA with attentional state (“in the zone” vs. “out of the zone”), absolute lag (1 to 29), and direction (forward vs. backward) as factors. We expected that we might find 1) an interaction between attentional state and absolute lag, indicating that nearby recall transitions would be more likely for items encoded “in the zone” vs. “out of the zone” and 2) an interaction between attentional state and direction, indicating a stronger forward asymmetry bias for items encoded “in the zone”. Note that we excluded four participants’ recall from this repeated-measures

ANOVA because they had no valid transitions (excluding repetitions and intrusions) from one “out of the zone” item to another.

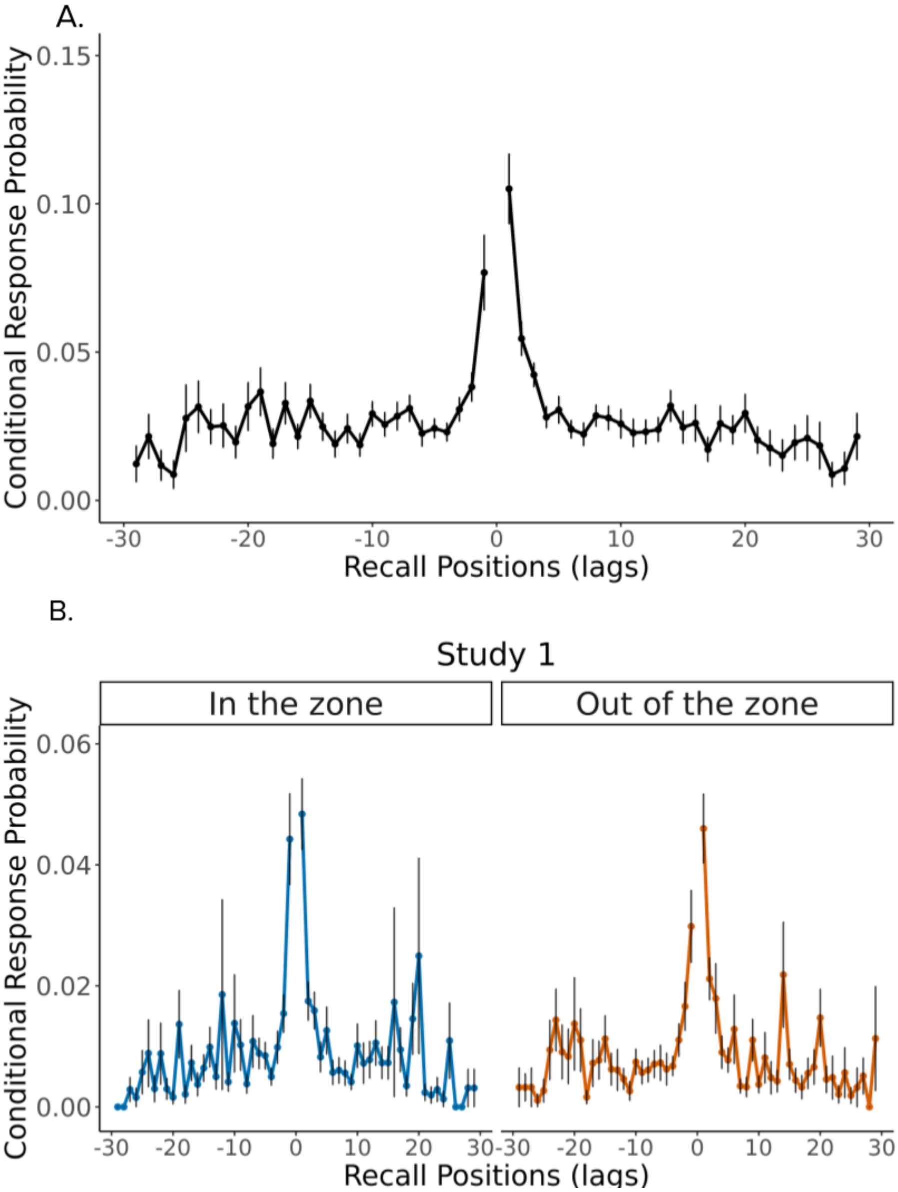

Figure 4. Lag-CRP curves overall and by attentional state for Study 1. **A.** Overall lag-CRP curve across participants and blocks. Individuals were more likely to recall items at nearby lags (i.e., the temporal contiguity effect, evidenced by a main effect of lag). Individuals were also marginally more likely to recall items in the forward vs backward direction for the closest lags (±1), indicating a weak forward asymmetry bias. **B.** Lag-CRP curves plotted separately for items encoded “in the zone” (left) and “out of the zone” (right). There was no difference between the two attentional states in the temporal contiguity or forward asymmetry of recall. Error bars represent the standard error.

We next examined forward asymmetry differences between the two attentional states at the nearby lags of ± 1. This was done to determine whether the lack of a forward asymmetry difference between the attentional states was due to inclusion of all lags in the CRP curves: forward symmetry is sometimes most pronounced for nearby lags. From a two-way repeated-measures ANOVA with lag (+1 vs. -1) and attentional state ("in the zone" vs. "out of the zone") as factors, we did not find an effect of attentional state ($F_{1,60} = 2.5$, $p = 0.12$, $\eta_p^2 = 0.04$) nor an interaction between attentional state and lag ($F_{1,60} = 1.92$, $p = 0.17$, $\eta_p^2 = 0.03$). All together, across these lag-CRP analyses, we did not find any differences in the temporal organization of recall for items encoded "in the zone" vs. "out of the zone".

Recall transitions within an event segment are more likely for items encoded "in the zone"

The lag-CRP analyses above examined temporal organization differences between the two attentional states, but they do not take into account qualitatively different types of transitions that could occur within an attentional state (such as transitions between different event segments) or transitions from one state to another (see **Figure 2**). However, it is possible that attentional fluctuations act in a similar way to event boundaries (Ezzyat & Davachi, 2010; DuBrow & Davachi, 2013, 2016; Heusser et al., 2018), such that recall is more temporally clustered within segments than across segments, and may occasionally "leap" between segments of a similar cognitive state (Chan et al., 2017).

We therefore examined recall as a function of the type of transition (**Figure 2**). If "in the zone" (vs "out of the zone") attentional states are more conducive to maintaining a temporal context representation, and this temporal context representation is reinstated every time an individual is "in the zone", two predictions could be made. First, that recall transitions within an "event segment" may be more likely for items encoded "in the zone" vs. "out of the zone" (i.e., same state, same event transitions; **Figure 2**), and second, that recall "leaps" to a different event segment in the same attentional state may be more likely for items encoded "in the zone" vs. "out of the zone" (i.e., same state, different event transitions).

To test this, for each type of transition ("same state, same event"; "same state, different event"; "different state, different event"), we calculated the number of transitions made during recall normalized by the number of opportunities to make such transitions (see **Methods: Recall Transitions by Event Segment**). We performed a two-way repeated-measures ANOVA with transition type (3 levels) and attentional state ("in the zone" vs. "out of the zone") as factors. We expected to find an interaction between attentional state and transition type. Specifically, we expected to find more "same state, same event" and "same state, different event" transitions for "in the zone" vs. "out of the zone" attentional states.

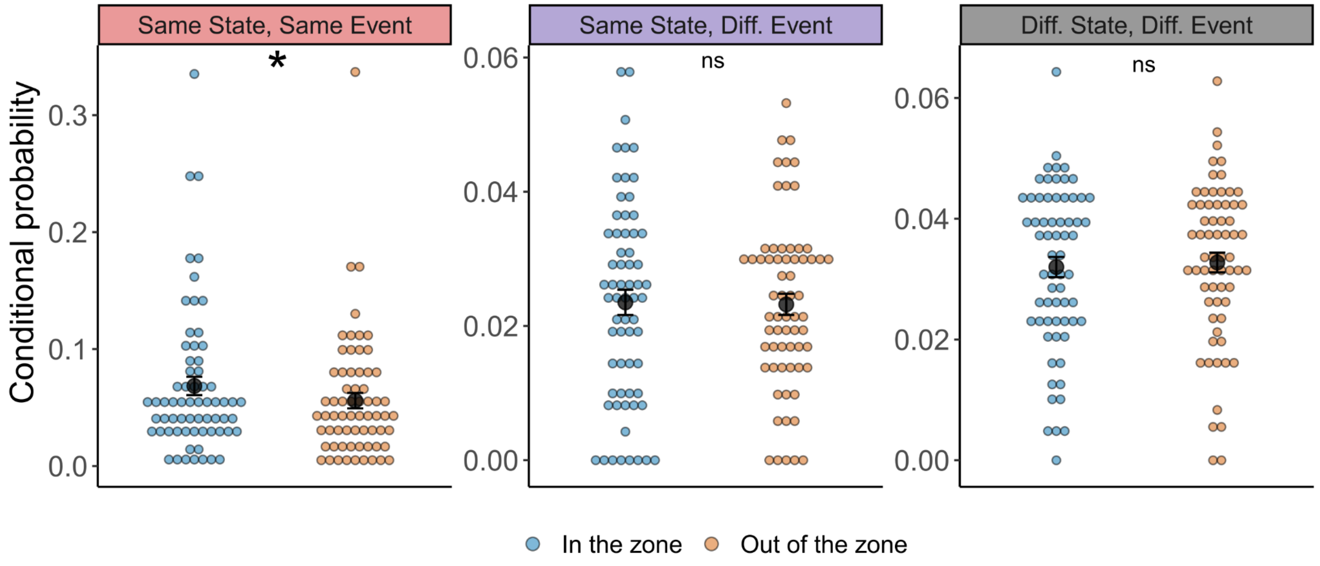

Figure 5. Recall transitions as a function of event type for Study 1. Recall transitions are shown based on whether they occurred within an "event segment" of a particular attentional state (same state, same event), across event segments of a given attentional state (same state, different event), or between attentional states (different state, different event; see **Figure 2**). "Same state, same event" transitions were more likely for items encoded "in the zone" vs. "out of the zone" (left panel). There were no significant differences in "same state, different event" or "different state, different event" transitions between the two attentional states (middle and right panels). Individual points indicate the conditional probability of each transition type (i.e., the number of times each transition type occurred divided by the number of opportunities to make a transition of that type) for each individual, separately for items encoded "in the zone" and "out of the zone". Black dots indicate the mean with standard error bars. *** $p < 0.001$. ns = not statistically significant.

From the repeated-measures ANOVA, we found a main effect of transition type ($F_{2,128} = 26.23$, $p < 0.0001$, $\eta_p^2 = 0.29$). We also found a main effect of attentional state ($F_{1,64} = 4.51$, $p = 0.04$, $\eta_p^2 = 0.07$) and a significant interaction between attentional state and transition type ($F_{2,128} = 4.17$, $p = 0.02$, $\eta_p^2 = 0.06$). These effects were not significantly different between the online and in-person samples (all *ps* > 0.10).

To understand this pattern of results, we conducted follow-up t-tests to compare all transition types between the two attentional states (**Figure 5**). As hypothesized, we found a significant difference in "same state, same event" transitions between the two attentional states ($t_{64} = 2.17$, $p = 0.03$, Cohen's dz = 0.27, 95% CI [0.001, 0.024]), such that participants made a greater proportion of “same state, same event” transitions for items encoded “in the zone” vs. “out of the zone”. This effect did not differ between in-person and online samples ($F_{1,63}$ = 0.008, p = 0.93 for the interaction of sample and attentional state for “same state, same event” transitions). However, contrary to our hypothesis, we did not find a significant difference between the two attentional states for “same state, different event” transitions (t_{64} = 0.15, p = 0.88, Cohen’s dz = 0.02, 95% CI [-0.003, 0.004]). “Different state, different event” transitions were also not significantly different between the two attentional states (t_{64} = 0.51, p = 0.61, Cohen’s dz = 0.06, 95% CI [-0.002, 0.004]). Thus, we did not find any evidence that recall for items encoded “in the zone” (vs. “out of the zone”) is more likely to “leap” from one event segment of that state to another.

Discussion

We hypothesized that “in the zone” attentional states, vs. “out of the zone” states, are more conducive to maintaining temporal context representations that can facilitate temporally organized recall. We found very limited support for this hypothesis. There was no difference between attentional states in overall recall, nor in forward asymmetry or temporal contiguity as assessed by the lag-CRP curves. However, analyses of recall transitions within and between “event segments” of each attentional state (**Figure 2**) revealed that individuals were more likely to make recall transitions to the same event segment when items were encoded “in the zone” vs. “out of the zone” (**Figure 5**). We sought to replicate this effect in Study 2.

We expected to see more recall “leaps” from one “in the zone” event segment to another (relative to “leaps” between “out of the zone” segments). This was inspired by findings showing that recall can “leap” between cognitively similar but temporally distant events (Chan et al., 2017). Although such recall “leaps” did occur, they did not occur more frequently for items encoded “in the zone” vs. “out of the zone”.

We replicated prior results in showing more online errors (in the encoding task) during “out of the zone” vs. “in the zone” attentional states. Yet, subsequent recall was not different overall between the two attentional states, and only one measure of recall organization showed a difference. One possibility is that our task only yielded moderate attentional fluctuations, which were only strong enough to produce subtle effects on recall. This may be because our task deviated from the original gradCPT in several ways (Rosenberg et al., 2011; Esterman et al., 2013). The original gradCPT requires a habitual response to frequent trials and a withheld response to infrequent trials. Here, we had participants provide a binary judgement (using one of two keys) on each trial, for which the responses were similar in frequency. Thus, the traditional manipulation might be more effective in inducing “out of the zone” states because 1) the same response is made most of the time and 2) the judgement used in the current task might be more difficult and subjective. Another difference is that our blocks were relatively short: 3 minutes relative to 8 minutes in a traditional gradCPT. These short blocks may not have induced strong enough attentional fluctuations to see large effects on recall organization. In Study 2, we modified our task to address these limitations.

Study 2

Overview

In Study 2, we sought to address limitations of Study 1 that may have made attentional fluctuations relatively weak and thus, limited our chance of seeing strong effects on subsequent recall. First, we changed our task to be aligned with the traditional gradCPT by using a go/no-go approach. Most trials were “go” trials in which a participant made a response to non-food items. On a minority of trials (“no-go”), which occurred 10% of the time, a food item was presented and participants had to withhold their response. This approach should make the “go” response habitual, making it more likely that individuals will “zone out” due to the repetitive nature of the task. Second, we made our encoding blocks longer (3 blocks of 8 minutes, rather than 5 blocks of 3 minutes in Study 1). This was done with the hope of encouraging stronger periods of “zoning out”.

Methods

Design

Participants

We report data from 68 participants (M_{age} = 22.62 ± 5.15, $M_{education}$ = 13.99 ± 1.65). 44 participants identified as female, 23 as male, and 1 as non-binary. In terms of race, 39 participants identified as White, 15 as Asian, 10 as Black or African American, and 4 as bi-racial. In terms of ethnicity, 60 participants identified as not Hispanic or Latino, and 8 identified as Hispanic or Latino. We do not report data from an additional 15 participants, who were excluded due to image loading errors (N = 3), low response rate during the encoding task (<80%, N = 7), outlier response accuracy during the encoding task (>3 SD from the group mean; N = 1), and recall recording issues (N = 4). Of the final sample, 48 participants were recruited from the Columbia University participant pool and the rest

(20 participants) were recruited through Prolific (www.prolific.co). All participants completed an online version of the task hosted on the Gorilla platform (www.gorilla.sc; Anwyl-Irvine et al., 2020). Informed consent was obtained in accordance with the Columbia University Institutional Review Board.

Stimuli

Stimuli were identical to Study 1 with the following exceptions. We chose 240 images instead of 191 from the pre-curated databases. Color images were converted to grayscale. 90% of the images (216 images) were non-food (i.e., inedible) items and 10% (24 images) were food items. No ambiguous stimuli were included (e.g., animals). The 240 images were divided into 3 lists of 80 images each (8 food, 72 non-food images). This was done manually by ensuring there were an equal number of items from a category (e.g., tools, furniture) in each list.

Procedure

The procedure was identical to Study 1 with the following exceptions. The experiment consisted of 3 blocks, each of which included a study phase, a distractor phase, and a recall phase (**Figure 1**). In each study phase, participants viewed 80 trial-unique items, which transitioned slowly from one into another as in Study 1. For each presented image, participants were asked to judge if the depicted object was "a food or non-food item". Importantly, they were asked to press a button when it was a non-food item (the dominant category), but withhold their response when it was a food item. This change aligned our task with the traditional gradCPT, such that participants habitually pressed one response 90% of the time, which may make it more likely for them to "zone out".

The distractor phase was identical to that in Study 1. The recall phase was similar to Study 1. Participants were initially given 2 minutes to verbally free recall items from the study phase. Unlike Study 1, after the initial 2 minutes of recording (the maximum allowed on Gorilla), participants were given the option to begin recording for another 2 minutes if they wanted to recall more objects. This was done because the blocks in Study 2 were longer than those in Study 1; thus, we wanted to give participants more time for free recall if they needed it.

Participants did not perform a practice block before beginning the task blocks, but were given video instructions on how to perform the task.

Analyses

Defining attentional states at encoding

Attentional states were defined using RTs for the judgements made by participants during study phase, in a procedure similar to Study 1. Unlike Study 1, however, participants were supposed to withhold responses on some trials; thus, some correct responses did not have an associated RT. Therefore, we first calculated — for correct trials with a response — the absolute deviation of the trial RT from the within-block mean, as in Study 1. Next, RT deviations for trials without a response (whether correctly withheld on "no-go" food trials or incorrectly withheld on "go" non-food trials) and trials with an incorrect response were interpolated from the two surrounding trials, as done in other studies employing this method (Esterman et al., 2013). All other steps were performed in an identical manner to Study 1. This resulted in trials being divided into two attentional states: "in the zone" states with lower RT variability (i.e., RTs closer to the mean) and "out of the zone" states with greater RT variability (i.e., RTs farther away from the mean; **Figure 6A**).

Errors at encoding

Similar to Study 1, we first sought to replicate the finding that "out of the zone" (vs. "in the zone") attentional states are associated with more errors (Rosenberg et al., 2011; Esterman et al., 2013). Errors in the encoding task were calculated as the sum of the number of incorrect button presses to a "no-go" food trial (commission errors) and the number of failures to respond to a "go" non-food trial (omission errors). We examined whether the number of errors made during "out of the zone" attentional states was greater than the number of errors made during "in the zone" states. Group-level analyses were conducted with a paired-samples t-test.

Recall performance

Recall performance and related analyses were identical to those in Study 1.

Temporal organization of recall

Analyses of temporal organization of recall were identical to those in Study 1. Note that in Study 1, actual and possible transitions ranged from -29 to +29 and the entire range was used in lag-CRP analyses. In Study 2, the range of actual and possible transitions is -79 to +79, because the length of the encoding list is 80 items. However, for the lag-CRP analyses of interest, we only used actual and possible transitions between -29 to +29. There were two reasons for this: First, transitions at the farther lags were rare (26 trials or fewer, across all 3 blocks for all 68 participants combined, for a given lag greater further away than ± 29), and hence the lag-CRP estimates were particularly noisy at those lags. Second, to facilitate comparison across studies, we opted to keep our analyses consistent by using the range from Study 1.

Recall Transitions by Event Segment

Analyses of recall transitions by event segment were identical to those in Study 1.

Results

Defining attentional states at encoding

In the encoding task, participants viewed images of objects and judged each as being a non-food item (with a button press) or a food item (by withholding a response). Overall, mean RT (defined from the onset of an image fading in; see **Methods**) was 3.57s (SD = 0.57). Median RT was 3.61s.

As before, we defined "in the zone" and "out of the zone" attentional states by performing a variance time course (VTC) analysis on the encoding phase RTs (see **Methods**). **Figure 6A** shows the VTC analysis for one sample participant in Study 2.

The mean length of an "in the zone" segment was 4.02 trials (SD = 0.45) and the mean length of an "out of the zone" segment was 3.99 trials (SD = 0.47; Note that each trial was 6 seconds long). The mean length of a segment did not differ between the two attentional states (t_{67} = 1.47, p = 0.15, Cohen's dz = 0.18, 95% CI [-0.01, 0.07]). The mean number of fluctuations within a block (i.e., the number of times participants transitioned from one state to another) was 19.11 (SD = 2.31). The number of trials within a segment ranged from 1 to 28 for "in the zone" states and from 1 to 21 for "out of the zone" states, across all blocks and participants.

These attentional states were used to examine accuracy on the encoding task and subsequent recall performance, described below.

More encoding errors during "out of the zone" attentional states

Participants performed very well on the encoding task ("Is this object food or a non-food item?"). They responded to 96.99% (SD = 4.08%) of the "go" non-food trials, which required a response. Mean accuracy (including correct responses on "go" trials and withheld responses on "no-go" trials) was 94.11% (SD = 4.66%).

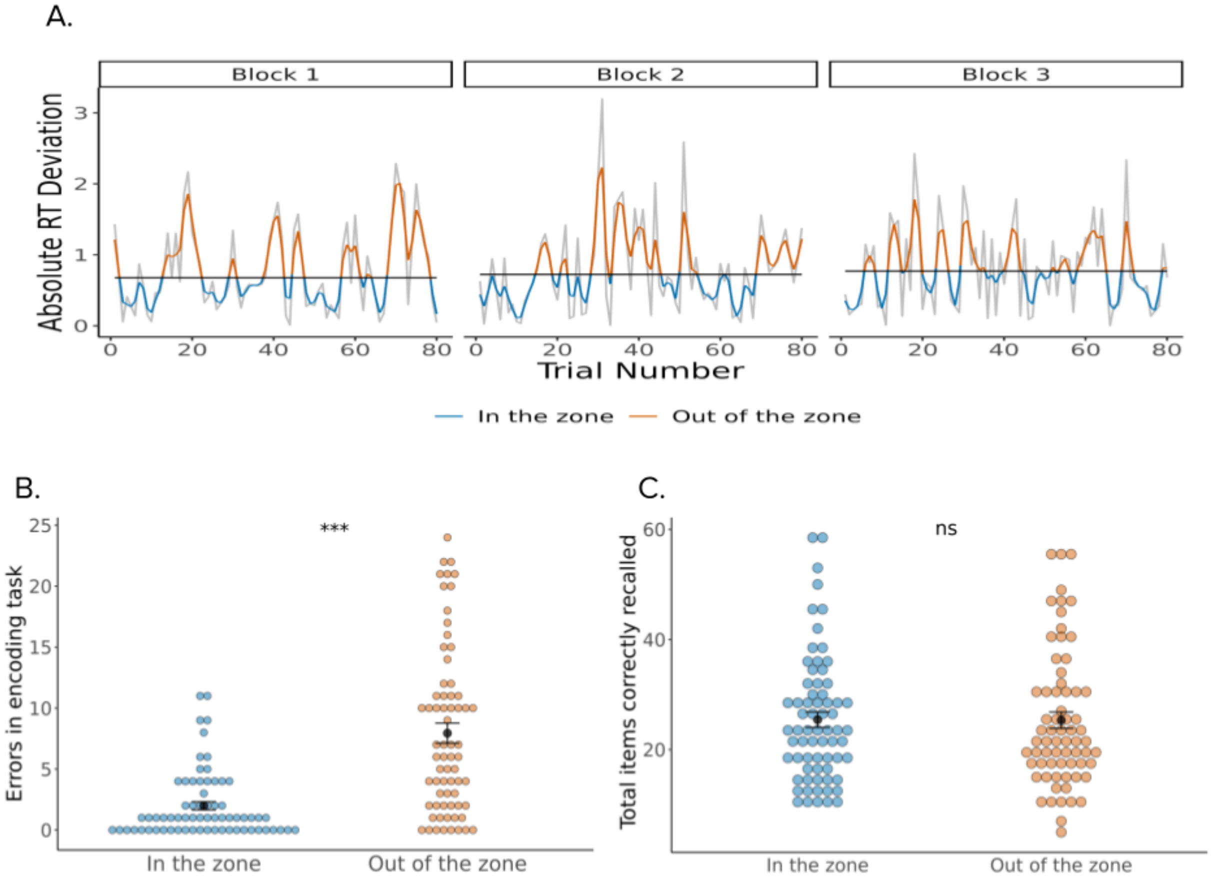

Figure 6. Encoding task performance and recall performance in Study 2. Encoding errors differ between attentional states but recall performance does not. **A.** Variance Time Course (VTC) analysis for a sample participant, depicting “in the zone” (blue) and “out of the zone” (orange) attentional states. Horizontal black lines indicate the median absolute RT deviation per block. Gray curves indicate raw (unsmoothed) RT deviation per block. **B.** Individual points show the number of encoding judgement errors made by each participant during “in the zone” and “out of the zone” attentional states. Participants made significantly more encoding errors during the “out of the zone” state. **C.** Individual points show the total number of items correctly recalled by each participant as a function of whether items were encoded “in the zone” or “out of the zone”. There was no difference in recall performance between the two states. Black points in panels B & C indicate the mean of the measure with standard error bars. *** $p < .0001$. ns = not statistically significant.

We next examined errors in the encoding task as a function of attentional state. We replicated prior studies (Rosenberg et al., 2011; Esterman et al., 2013) and Study 1: A paired samples t-test revealed that participants made significantly more encoding errors during an “out of the zone” attentional state (mean ± SD: 7.94 ± 6.82) compared to an “in the zone” attentional state (1.99 ± 2.74; $t_{67} = 8.52$, $p < 0.0001$, Cohen’s dz = 1.03, 95% CI [4.56, 7.35], **Figure 6B**). Thus, the VTC analysis remains successful in identifying fluctuations between better and worse attentional states.

Overall recall does not differ between the two attentional states

We next turned to examining memory for the objects encoded during the study phase. Mean recall was 51.32 (SD = 23.29); mean recall within a block was 17.11 (SD = 7.76).

We then separately examined recall based on whether items were encoded “in the zone” or “out of the zone”. As in Study 1, we did not find a significant difference in recall performance between “in the zone” (Mean ± SD: 25.43 ± 11.58) and “out of the zone” (25.34 ± 12.32) attentional states ($t_{67} = 0.12$, $p = 0.91$, Cohen’s dz =0.02, 95% CI [-1.43, 1.60], **Figure 6C**). Thus, as in Study 1, these states differed in performance during the encoding task but showed no differences in subsequent recall.

No differences in temporal contiguity or forward asymmetry between the two attentional states

Figure 7A shows the overall lag-CRP curve, across participants and blocks, regardless of attentional state at encoding. To test for typical properties of lag-CRP curves, we conducted a two-way repeated-measures ANOVA on the lag-CRP measures (i.e., lag-conditional recall) with absolute lag (1 to 29) and direction (forward vs. backward) as factors. The Greenhouse-Geisser correction was applied to the absolute lag effects, which violated the assumption of sphericity. We found a significant main effect of absolute lag ($F_{11.48, 769.16} = 14.47$, $p < 0.0001$, $\eta_p^2 = 0.18$): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. We also found a significant main effect of direction ($F_{1,67} = 15.77$, $p < 0.001$, $\eta_p^2 = 0.19$) and an interaction between absolute lag and direction ($F_{15.96,1069.32} = 1.88$, $p = 0.02$, $\eta_p^2 = 0.03$). The main effect of direction was due to greater likelihood of recalling items in a forward vs. backward direction. The absolute lag by direction interaction arose because this forward asymmetry was more pronounced for closer lags. A paired-samples t-test on the CRP values for +1 and -1 lags also revealed a significant difference ($t_{67} = 3.59$, $p < 0.001$, Cohen’s dz = 0.44, 95% CI [0.01, 0.04]) such that CRP was greater for +1 compared to -1 lags, again confirming the forward asymmetry bias. Thus, we were able to replicate the temporal contiguity effect and the forward asymmetry bias in recall.

We next tested our primary hypothesis that a good (vs. bad) attentional state at encoding would be related to better temporal organization of subsequent recall, evidenced as greater temporal contiguity effects and/or greater forward asymmetry bias. As in Study 1, we constructed separate lag-CRP curves for “in the zone” vs. “out of the zone” attentional states based on successive recall of items encoded in the same state (**Figure 7B**). We conducted a three-way repeated-measures

ANOVA with attentional state ("in the zone" vs. "out of the zone"), absolute lag (1 to 29), and direction (forward vs. backward) as factors.

We found a significant main effect of absolute lag ($F_{10.36,694.12} = 17.30$, $p < 0.0001$, $\eta_p^2 = 0.09$): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. We also found a significant main effect of direction ($F_{1,67} = 3.38$, $p = 0.007$, $\eta_p^2 = 0.05$) and an interaction between direction and absolute lag ($F_{13.44,900.48} = 3.04$, $p = 0.0002$, $\eta_p^2 = 0.04$). Thus, as in the overall lag-CRP curve (**Figure 7A**), CRP curves plotted separately for each attentional state (**Figure 7B**) confirmed that participants were more likely to recall items in the forward vs. backward direction, with this asymmetry being more pronounced for closer vs. farther lags.

We next examined main effects and interactions involving attentional state. There was no main effect of attentional state ($F_{1,67} = 0.80$, $p = 0.38$, $\eta_p^2 = 0.01$). There was also no interaction between attentional state and direction ($F_{1,67} = 0.0004$, $p = 0.98$, $\eta_p^2 = 0.00001$), no interaction between attentional state and absolute lag ($F_{12.04,806.68} = 0.99$, $p = 0.46$, $\eta_p^2 = 0.02$), nor a three-way interaction between absolute lag, direction, and attentional state ($F_{13.44,900.48} = 1.26$, $p = 0.23$, $\eta_p^2 = 0.02$). Hence, we did not see any differences in temporal contiguity or forward asymmetry bias of recall for items encoded "in the zone" vs. "out of the zone".

We conducted a follow-up analysis to compare the two attentional states at the lags of ± 1. This was done to examine whether including all lags in our repeated-measures ANOVA masked any differences between the states that were more specific to close recall transitions. From a two-way repeated-measures ANOVA with lag (+1 vs. -1) and attentional state ("in the zone" vs. "out of the zone") as factors, we found only a significant main effect of lag ($F_{1,67} = 15.06$, $p < 0.001$, $\eta_p^2 = 0.18$). The main effect of attentional state ($F_{1,67} = 0.001$, $p = 0.98$, $\eta_p^2 = 0.0001$), and the interaction between attentional state and lag, were not statistically significant ($F_{1,67} = 0.63$, $p = 0.43$, $\eta_p^2 = 0.009$). The significant main effect of lag (+1 vs. -1) indicated that individuals are more likely to make forward vs. backward transitions, even at the closest lag; this reproduces our findings above with overall recall organization. However, this forward asymmetry at the ± 1 lags was not different between the two states.

All together, across these analyses, we replicated the finding that recall is temporally organized. However, this temporal organization was not different between the two attentional states.

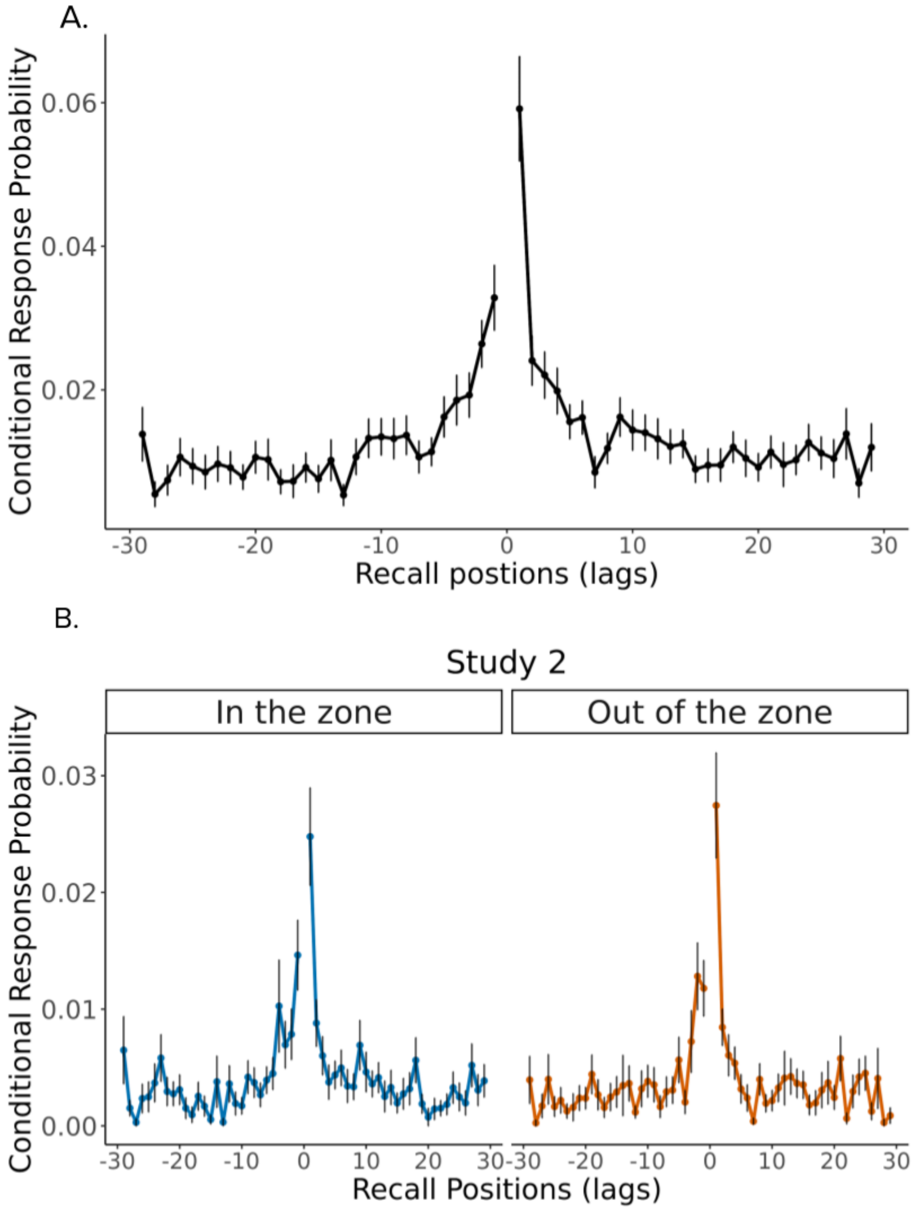

Figure 7. Lag-CRP curves overall and by attentional state for Study 2. **A.** Overall lag-CRP curve across participants and blocks. Individuals were more likely to recall items at nearby lags (main effect of lag), and showed a bias to recall in the forward direction (main effect of direction), moreso for nearby lags (lag x direction interaction). **B.** Lag-CRP curves plotted separately for items encoded "in the zone" (left) and "out of the zone" (right). There was no difference between the two attentional states in the temporal organization of recall (neither temporal contiguity nor forward asymmetry). Error bars represent the standard error.

No differences in event transition types between the two attentional states

As in Study 1, we next examined recall as a function of the type of transition (**Figure 2 and Study 1 Methods: Recall Transitions by Event Segment**). We performed a two-way repeated-measures

ANOVA on the conditional probability of recall transitions with transition type (3 levels) and attentional state ("in the zone" vs. "out of the zone") as factors. We expected to replicate the main effect of attentional state, and the attentional state by transition type interaction, that we observed in Study 1.

We found a main effect of transition type ($F_{2,134} = 45.02$, $p < 0.0001$, $\eta_p^2 = 0.40$). The main effect of attentional state ($F_{1,67} = 0.001$, $p = 0.97$, $\eta_p^2 = 0.00001$) and the interaction between attentional state and transition type ($F_{2,134} = 0.06$, $p = 0.95$, $\eta_p^2 = 0.0009$) were not statistically significant. This suggests that, unlike Study 1, each type of recall transition was not different for items encoded "in the zone" and "out of the zone" (**Figure 8**).

Given the main effect of transition type, we conducted follow-up t-tests to compare them, collapsing across the two attentional states. We found that: 1) "same state, same event" recall transitions were significantly more likely than "same state, different event" recall transitions ($t_{67} = 8.22$, $p < 0.001$, Cohen's dz = 1.00, 95% CI [0.013, 0.024]) and "different state, different event" recall transitions ($t_{67} = 7.22$, $p < 0.001$, Cohen's dz = 0.87, 95% CI [0.013, 0.025]), and 2) "different state, different event" transitions were significantly more likely than "same state, different event" transitions ($t_{67} = 2.78$, $p = 0.007$, Cohen's dz = 0.34, 95% CI [0.0003, 0.002]).

This pattern of results is consistent with the temporal contiguity effect: participants are more likely to make recall transitions to nearby items. In particular, items encoded in the same state and same event are the closest ("same state, same event" transitions; e.g., recall transitions within Event 1 in **Figure 2**), followed by items in an adjacent event segment of a different attentional state (adjacent "different state, different event" transitions; e.g., recall transitions between items in Event 1 and Event 2 in **Figure 2**), and then last, recall "leaps" to items in a distant event segment of the same attentional state ("same state, different event" transitions; e.g., recall transitions between items in Event 1 and Event 3 in **Figure 2**).

Thus, across these event transition analyses, we failed to find evidence for our initial hypotheses regarding differences between "in the zone" and "out of the zone" states, and did not replicate the results from Study 1.

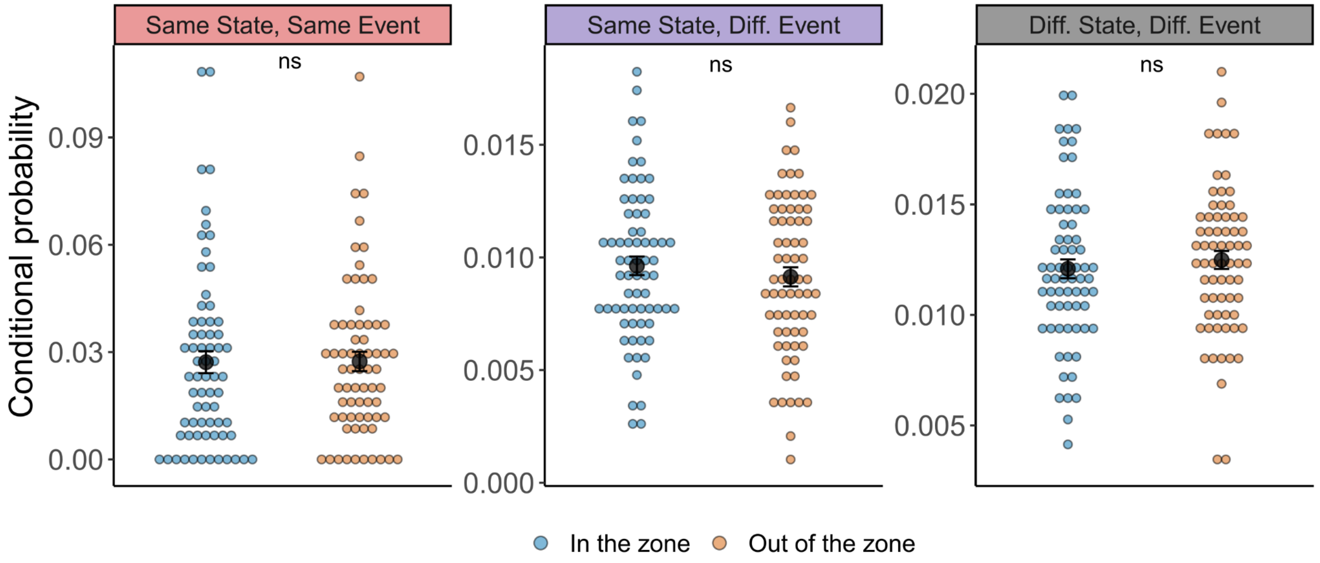

Figure 8. Recall transitions as a function of event type in Study 2. Recall transitions are shown based on whether they occurred within an "event segment' of a particular attentional state (same state, same event), across event segments of a given attentional state (same state, different event), or between attentional states (different state, different event; see **Figure 2**). There were no significant differences between the two attentional states in any transition type. Individual points indicate the conditional probability of recall transitions for each transition type (i.e., the number of times each transition type occurred divided by the number of opportunities to make a transition of that type) for each individual, separately for items encoded "in the zone" and "out of the zone". Black dots indicate the mean with standard error bars. ns = not statistically significant.

Discussion

In Study 2, we made adjustments to our task to try to encourage stronger attentional fluctuations, in particular stronger "zoning out". As before, we hypothesized that "in the zone" attentional states, vs. "out of the zone" states, aid in maintenance of temporal context representations, thus facilitating temporally organized recall. However, we did not find any evidence to support this hypothesis. While we observed differences in encoding task performance, with more errors for "out of the zone" states (replicating prior work by Esterman et al., 2013), we did not find any differences in our recall measures of interest. There was no statistically significant difference in overall recall performance for items encoded during "in the zone" vs. "out of the zone" attentional states. Furthermore, while we replicated prior work in showing both temporal contiguity and forward asymmetry effects in recall, we did not see any differences between the two attentional states in these effects. Finally, we found no differences between the two attentional states in recall transitions between different event types (**Figure 2**).

Taken together, we failed to find any evidence that “in the zone” vs. “out of the zone” attentional states have a differential impact on the temporal organization of recall. This was despite our changes to study design that made it more similar to the original gradCPT procedure (see **Study 1: Discussion**). Indeed, we found *more* evidence for the differential impact of “in the zone” vs “out of the zone” attentional states in Study 1. We were unable to replicate the effect observed in that study: more “same state, same event” transitions for items encoded “in the zone” vs “out of the zone”. Thus, the significant result from Study 1 may have been a false positive, or alternatively, is contingent on the specific task design used in Study 1.

Why did we fail to find effects of attentional states on recall in Study 2? One possibility is that, despite longer blocks, making semantic judgments (food vs. non-food item) may have been challenging enough to engage participants’ sustained attention and hence, did not produce strong periods of “zoning out” as we hoped. In contrast, the traditional gradCPT often has participants perform a more perceptual task (e.g., male or female face). The semantic judgement may also encourage semantic clustering (Long & Kahana, 2017), which may interfere with our ability to detect differences in the temporal structure of recall between the two attentional states. Finally, it is possible that the gradual transitions between items — a core part of the gradCPT — have an unintended effect of making the task somewhat engaging, in that participants can try to identify objects at lower and lower opacities as the task goes on. Such gradual transitions also make our task less similar to standard list-learning recall tasks, which present each item in isolation. We address these limitations in Study 3.

Study 3

Overview

In Study 3, we made the following changes to address the limitations above. First, we changed the encoding judgement to be a perceptual one (i.e., is the image color or grayscale?) instead of a semantic one. This aligned our approach with the traditional gradCPT, which uses perceptual judgements (e.g., male or female face?). We also made this change to ensure that the task judgement does not encourage semantic clustering of items (Long & Kahana, 2017). For example, if participants in Study 2 attempted to cluster food items together, and non-food items together, we may have had less of an opportunity to observe subtle differences in temporal clustering between the two attentional states. Second, we removed the gradual transitions between items, and replaced this transition with a relatively long presentation duration (3s on the screen, with a 2s inter-item interval). This change makes our design more similar to standard memory tasks, and may additionally make the task less engaging. Finally, in an attempt to improve recall performance, we reduced the length of our study phase (60 items instead of the 80 in Study 2).

Methods

Design

Participants

We report data from 68 participants (M_{age} = 20.09 ± 2.20, $M_{education}$ = 14.03 ± 1.46). 33 participants identified as female and 35 as male. In terms of race, 35 participants identified as White, 19 as Asian, 7 as Black or African American, 4 as bi-racial, 1 as American Indian/Alaskan Native, and 2 as Other. In terms of ethnicity, 54 participants identified as not Hispanic or Latino, and 14 identified as Hispanic or Latino. We do not report data from an additional 4 participants, who were excluded due to low response rate during the encoding task (<80%, N = 1), age greater than 40 years (N = 1), recall recording issues (N = 1) and incomplete participation (N = 1). All participants were recruited from the Columbia University participant pool and participated in an online version of the task hosted on the Gorilla platform (www.gorilla.sc; Anwyl-Irvine et al., 2020). Informed consent was obtained in accordance with the Columbia University Institutional Review Board.

Stimuli

Stimuli were identical to Study 2 with the following exceptions. We chose 180 objects from the pre-curated databases. Of these, 10% of the images (18 images) were converted to grayscale. 90% of the images (162 images) were in color. The 180 images were divided into 3 lists of 60 images each (6 grayscale images, 54 color images). This was done manually by ensuring there were an equal number of items from a category (e.g., tools, furniture) in each list.

Procedure

The procedure was identical to Study 2 with the following exceptions (**Figure 1**). In each study phase, participants viewed 60 trial-unique items from the created lists. Each image was presented for 3s followed by a fixation cross during the 2s inter-item interval (i.e., there was no gradual fading between images). Participants were asked to judge if each image was in color or grayscale: They pressed a button when it was in color, but withheld their response when it was in grayscale.

Participants therefore habitually pressed one response 90% of the time. The distractor and recall phases were identical to the ones in Study 2.

Analyses

All analyses were identical to Study 2, except that response times (RTs) were defined from the onset of the static image on each trial (because there was no fading in).

Results

Defining attentional states at encoding

In the encoding task, participants viewed images and judged each as being in color (with a button press) or grayscale (by withholding their response). Overall, mean response time (RT; defined from image onset) was 1.32s (SD = 0.20). Median RT was 1.30s. As in Studies 1 and 2, we performed a variance time course analysis on the encoding phase RTs. **Figure 9A** shows the VTC analysis for one sample participant in Study 3.

The mean length of an "in the zone" segment was 3.85 trials (SD = 0.53) and the mean length of an "out of the zone" segment was 3.81 trials (SD = 0.47; Note that each trial was 5 seconds long). The mean length of a segment did not differ between the two attentional states (t_{67} = 1.34, p = 0.18, Cohen's dz = 0.04, 95% CI [-0.02, 0.10]). The mean number of fluctuations within a block (i.e., the number of times participants transitioned from one state to another) was 14.84 (SD = 2.1). The number of trials within a segment ranged from 1 to 18 for "in the zone" states and from 1 to 20 for "out of the zone" states, across all blocks and participants.

These attentional states were used to examine accuracy on the encoding task and subsequent recall performance, described below.

No difference in encoding errors during "in the zone" vs "out of the zone" attentional states

Participants performed very well on the encoding task ("Is this image in color or grayscale?"). They responded to 98.80% (SD = 2.58%) of the "go" color image trials, which required a response. Mean accuracy (defined as correct responses on "go" trials and withheld responses on "no-go" trials) was 97.45% (SD = 2.61%).

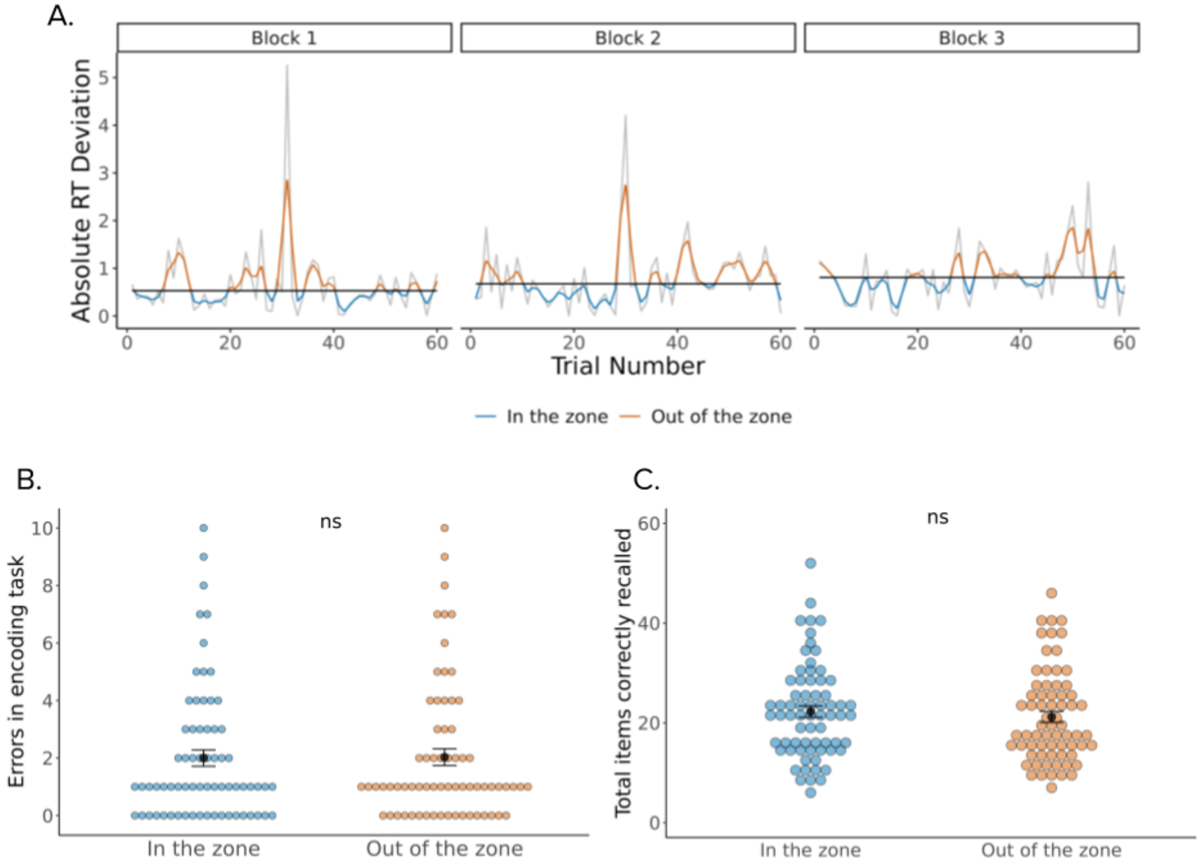

Figure 9. Encoding task performance and recall performance in Study 3. Neither encoding errors nor recall performance differ between attentional states. **A.** Variance Time Course (VTC) analysis for a sample participant depicting "in the zone" (blue) and "out of the zone" (orange) attentional states. Horizontal black lines indicate the median absolute RT deviation per block. Gray curves indicate raw (unsmoothed) RT deviation per block. **B.** Individual points show the number of encoding judgement errors made by each participant during "in the zone" and "out of the zone" attentional states. The number of encoding errors did not differ between "in the zone" vs. "out of the zone" attentional states. **C.** Individual points show the total number of items correctly recalled by each participant as a function of whether items were encoded "in the zone" or "out of the zone". There was no difference in recall performance between the two states. Black points in panels B & C indicate the mean of the measure with standard error bars. ns = not statistically significant.

We next examined errors in the encoding task as a function of attentional state. Surprisingly, we failed to replicate Studies 1 and 2: A paired samples t-test revealed that the number of encoding errors during an "out of the zone" attentional state (mean ± SD: 2.03 ± 2.40) was not significantly different from that in an "in the zone" attentional state (2.00 ± 2.34); (t_{67} = 0.10, p = 0.92, Cohen's dz = 0.51, 95% CI [-0.54,0.60], **Figure 9B**). Thus, unlike Studies 1 and 2, and unlike prior studies (Rosenberg et al., 2011; Esterman et al., 2013), the VTC analysis was unsuccessful in identifying fluctuations between better and worse attentional states. Although removing gradual transitions made our design more similar to standard memory tasks, the abrupt image onsets may have captured attention, reducing "zoning out" (Esterman et al., 2013). We return to this issue in the **Discussion**. Despite this null result, we report the rest of Study 3 results for completeness.

No differences in temporal contiguity or forward asymmetry between the two attentional states

As in Studies 1 and 2, we examined lag-CRP curves to explore the temporal organization of recall. This allowed us to determine whether the structure of memory differed between the two attentional states, even if overall memory performance did not.

Figure 10A shows the overall lag-CRP curve, across participants and blocks, regardless of attentional state at encoding. To test for typical properties of lag-CRP curves, we again conducted a two-way repeated-measures ANOVA on the lag-CRP measures (i.e., lag-conditional recall) with absolute lag (1 to 29) and direction (forward vs. backward) as factors. The Greenhouse-Geisser correction was applied to the absolute lag effects because they violated the assumption of sphericity. We found a significant main effect of absolute lag ($F_{11.48,\ 769.16} = 11.49$, $p < 0.0001$, $\eta_p^2 = 0.15$): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. There was no main effect of direction ($F_{1,67} = 0.002$, $p = 0.97$, $\eta_p^2 = 0.19$). However, there was a significant interaction between absolute lag and direction ($F_{15.96,1069.32} = 1.84$, $p = 0.02$, $\eta_p^2 = 0.03$): Participants were more likely to recall items in a forward vs. backward direction but particularly for closer lags. A paired-samples t-test on the CRP values for +1 and -1 lags also revealed a significant difference ($t_{67} = 3.32$, $p = 0.002$, Cohen's dz = 0.40, 95% CI [0.01, 0.04]): CRP was greater for +1 vs. to -1 lags. Thus, we were able to replicate the temporal contiguity effect and the forward asymmetry bias of recall.

We next tested our primary hypothesis that a good (vs. bad) attentional state at encoding would be related to better temporal organization of subsequent recall. As before, we constructed separate lag-CRP curves for "in the zone" vs. "out of the zone" attentional states based on successive recall of items encoded in the same state (**Figure 10B**). We conducted a three-way repeated-measures ANOVA with attentional state ("in the zone" vs. "out of the zone"), absolute lag (1 to 29), and direction (forward vs. backward) as factors. As before, we expected to find interactions between attentional state and absolute lag and/or direction. One participant was excluded from this analysis because they did not have any successive recall transitions between items encoded during an “in the zone” attentional state.

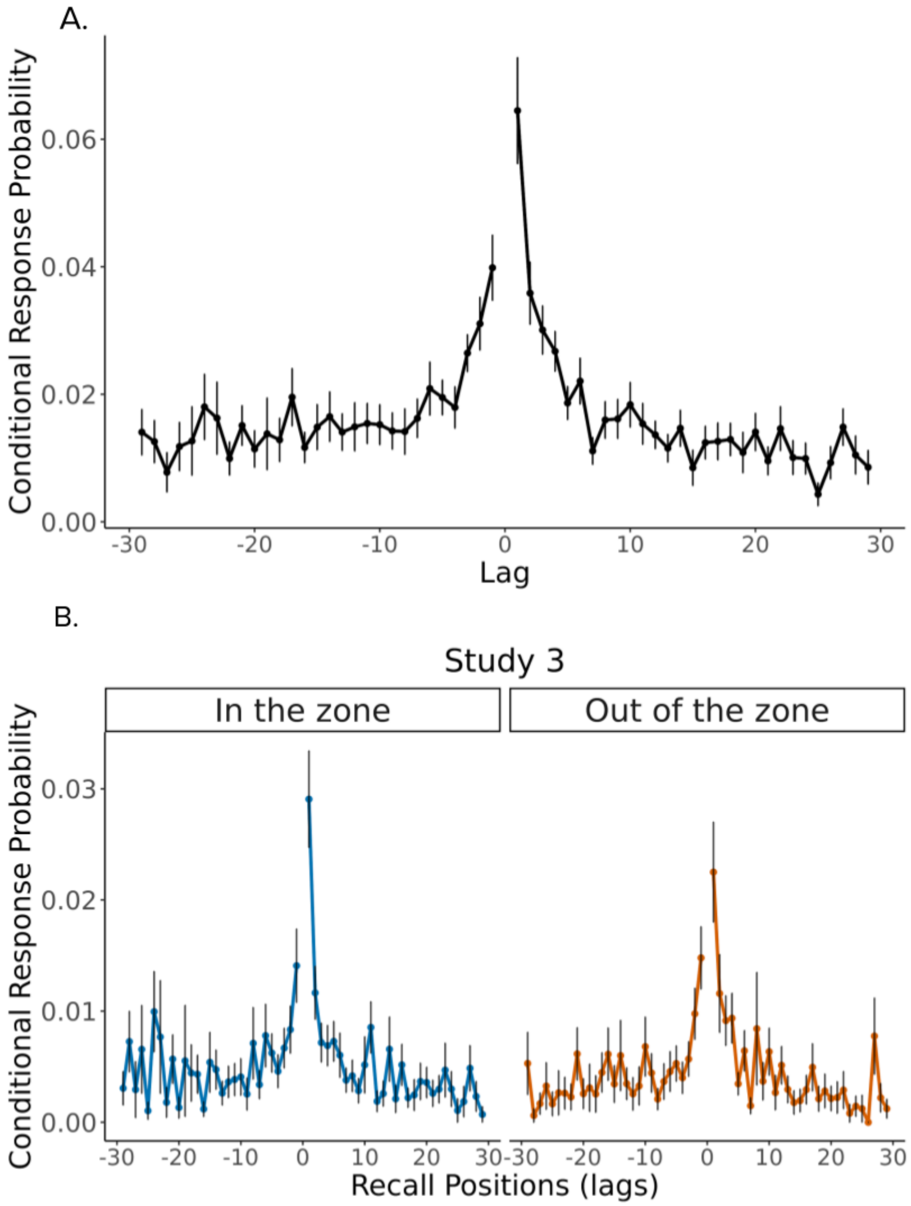

Figure 10. Lag-CRP curves overall and by attentional state for Study 3. **A.** Overall lag-CRP curve across participants and blocks. Individuals were more likely to recall items at nearby lags (main effect of lag), and showed a bias to recall in the forward direction (i.e., positive lags), moreso for nearby lags (lag x direction interaction). **B.** Lag-CRP curves plotted separately for items encoded “in the zone” (left) and “out of the zone” (right). There was no difference between the two attentional states in the temporal organization of recall (neither temporal contiguity nor forward asymmetry). Error bars represent the standard error.

From the three-way repeated-measures ANOVA, we found a significant main effect of absolute lag ($F_{10.92,720.72} = 10.04$, $p < 0.0001$, $\eta_p^2 = 0.13$): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. There was no main effect of direction ($F_{1,66} = 0.09$, $p = 0.76$, $\eta_p^2 = 0.001$), but there was a significant interaction between direction and absolute lag ($F_{14,924} = 2.18$, $p = 0.007$, $\eta_p^2 = 0.03$). As for the overall lag-CRP curve, participants were more likely to recall items in the forward vs. backward direction, with this asymmetry being greater for closer vs. farther lags. There was no main effect of attentional state ($F_{1,66} = 1.79$, $p = 0.19$, $\eta_p^2 = 0.03$). There was also no interaction between attentional state and direction ($F_{1,66} = 0.16$, $p = 0.69$, $\eta_p^2 = 0.002$), no interaction between attentional state and absolute lag ($F_{14.84,979.44} = 0.81$, $p = 0.67$, $\eta_p^2 = 0.012$), nor a three-way interaction between absolute lag, direction, and attentional state ($F_{15.12,997.92}= 0.92$, $p = 0.54$, $\eta_p^2 = 0.01$). Hence, we did not see any differences in recall organization — neither temporal contiguity nor forward asymmetry bias — based on attentional state at encoding.

As before, we conducted a follow-up analysis to examine differences between the two attentional states at the nearby lags of ± 1. From a two-way repeated-measures ANOVA with lag (+1 vs. -1) and attentional state (“in the zone” vs. “out of the zone”) as factors, we found only a significant main effect of lag ($F_{1,66} = 12.6$, $p = 0.0007$, $\eta_p^2 = 0.16$). The main effect of attentional state ($F_{1,66} = 0.55$, $p = 0.46$, $\eta_p^2 = 0.008$), and the interaction between attentional state and lag, was not statistically significant ($F_{1,66} = 1.32$, $p = 0.26$, $\eta_p^2 = 0.02$). The significant main effect of lag (+1 vs. -1) confirms that individuals are more likely to make more forward vs. backward transitions at the closest lag, as demonstrated above with the analysis of overall recall performance. However, forward asymmetry at the ± 1 lags was not different between the two states.

We therefore once again replicated the finding that recall is temporally organized. However, the temporal organization of recall was not different between the two attentional states. This replicates the null findings from the lag-CRP analyses in Studies 1 and 2.

No differences in event transition types between the two attentional states

As in Studies 1 and 2, we next examined recall transitions as a function of the type of event segment (see **Figure 2** and **Study 1 Methods: Recall Transitions by Event Segment**).

To do this, we performed a two-way repeated-measures ANOVA with transition type (3 levels) and attentional state (“in the zone” vs. “out of the zone”) as factors. As before, we hypothesized that “same state, same event” and “same state, different event” transitions may be more likely for items encoded “in the zone” vs. “out of the zone”.

We found a main effect of transition type ($F_{2,134} = 26.49$, $p < 0.0001$, $\eta_p^2 = 0.28$). The main effect of attentional state ($F_{1,67} = 1.39$, $p = 0.24$, $\eta_p^2 = 0.02$), and the interaction between attentional state and transition type ($F_{2,134} = 1.30$, $p = 0.28$, $\eta_p^2 = 0.02$), were not statistically significant. Thus, each type of recall transition was not differentially likely for items encoded “in the zone” and “out of the zone” (**Figure 11**).

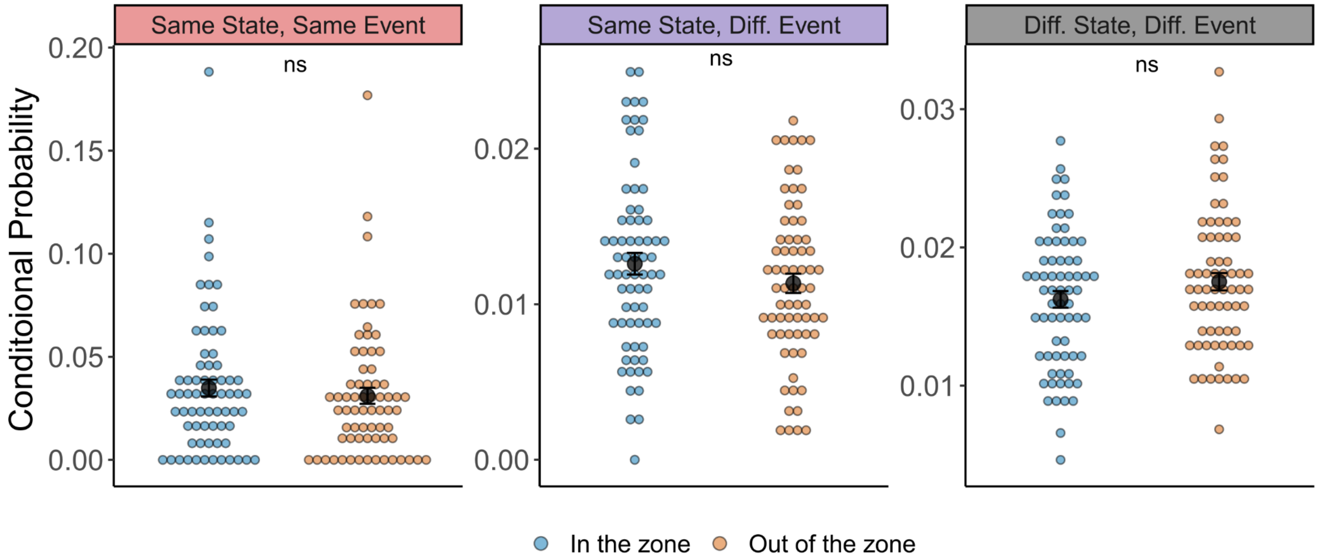

Figure 11. Recall transitions as a function of event type in Study 3. Recall transitions are shown based on whether they occurred within an “event segment’ of a particular attentional state (same state, same event), across event segments of a given attentional state (same state, different event), or between attentional states (different state, different event; see **Figure 2).** There were no significant differences in any transition type between the two attentional states. Individual points indicate the conditional probability of each transition type (i.e., the number of times each transition type occurred divided by the number of opportunities to make a transition of that type) for each individual, separately for items encoded “in the zone” and “out of the zone”. Black dots indicate the mean with standard error bars. ns = not statistically significant.

As for Study 2, we conducted follow-up t-tests to understand the main effect of transition types, collapsing across the two attentional states. We found that: 1) “same state, same event” recall transitions were significantly more likely compared to “same state, different event” recall transitions ($t_{67} = 6.10$, $p < 0.0001$, Cohen’s dz = 0.74, 95% CI [0.015, 0.029]) and “different state, different event” recall transitions ($t_{67} = 5.65$, $p < 0.0001$, Cohen’s dz = 0.69 , 95% CI [0.013, 0.026]), and 2) “different state, different event” transitions were significantly more likely compared to “same state, different event" transitions ($t_{67} = 3.47$, $p = 0.0009$, Cohen's dz = 0.42, 95% CI [0.001, 0.004]). This is consistent with temporally structured recall: the closest recall transitions are to items in the "same state, same event", followed by items in an adjacent event segment but a different attentional state (an adjacent "different state, different event"), and further away are items in the same attentional state but a different event segment ("same state, different event"). These results replicate Study 2.

As in Study 2, however, we did not find any evidence that these recall transition types differed between the two attentional states. We therefore did not replicate Study 1, which showed more "same state, same event" transitions for items encoded "in the zone" vs. "out of the zone".

Discussion

In Study 3, we made further adjustments to our task to encourage more "zoning out" and to make our procedure more similar to standard list-learning recall tasks. We again tested the hypothesis that "in the zone", vs. "out of the zone", states aid in maintenance of temporal context representations, thus encouraging temporally organized recall. However, we did not find any evidence to support this hypothesis.

Contrary to Studies 1 and 2, we did not observe any differences in encoding task performance across the two attentional states. Why might this be the case? First, we removed the gradual transitions between images. Although we hoped that would make the task more boring, the abrupt image onsets could have captured attention, thus preventing participants from "zoning out" (Rosenberg et al., 2011; Esterman et al., 2013). Second, long and variable inter-stimulus durations result in more attentional lapses than short, fixed durations (Unsworth et al., 2018). Our short and fixed ITI (2 seconds) may therefore have made it less likely that participants would zone out. Finally, we changed the encoding judgement to a simple perceptual judgement. Although this change made our task more similar to the traditional gradCPT, which often uses perceptual judgments, it had the effect of increasing the accuracy of encoding judgements. Having such a low error rate (~2 errors, on average, per participant in each attentional state) may have hurt our chances of seeing differences between the two states. This null finding makes it difficult to interpret the lack of differences between attentional states in subsequent recall performance, because we simply may not have induced attentional fluctuations at all. This prompted us to conduct Study 4, which is similar to Study 2, with some minor changes to once again try to induce stronger attentional fluctuations.

Study 4

Overview

In Study 3, online task performance was not different between “in the zone” and “out of the zone” states. This makes the null effects in recall organization difficult to interpret, because we may not have successfully differentiated between better and worse attentional states. We therefore conducted another study with the gradual transitions used in Studies 1 and 2, in which we successfully replicated prior work showing more errors during “out of the zone” states (Rosenberg et al., 2011; Esterman et al., 2013). Study 4 used a similar design as Study 2 (go/no-go procedure, with responses for non-food items and withheld responses for food ites of 120 images each (instead of 3 blocks of 80 items each), and second, the trial duration (from an image fading into being 100% clear) was reduced from 6s to 4s. Both of these changes were implemented to bring our design closer to the traditional gradCPT, which typically uses fast presentation durations and many trials. In this way, we hoped to induce stronger attentional fluctuations.

Methods

Design

Participants

Pilot data using the Study 4 procedure revealed that participants had worse recall performance than our earlier studies (likely because Study 4 blocks were longer than those in our prior studies). We therefore opted to collect a larger sample size, so that summed recall performance across all participants would be comparable to Study 2 (Baker et al., 2020). We report data from 124 participants (M_{age} = 21.42 ± 6.26, $M_{education}$ = 13.63 ± 1.54). 84 participants identified as female, 37 as male, 2 as non-binary, and 1 did not specify. In terms of race, 67 participants identified as White, 30 as Asian, 14 as Black or African American, 4 as bi-racial, 3 as Native American or Alaskan Native, 3 as Hispanic/Latino, 1 as Middle-Eastern, and 2 did not specify. In terms of ethnicity, 98 participants identified as not Hispanic or Latino, and 26 identified as Hispanic or Latino. We do not report data from an additional 32 participants, who were excluded due to image loading errors (N = 1), low response rate during the encoding task (<80%, N = 20), recall recording issues (N = 10), and no recall (N = 1). Of the final sample, 5 participants were recruited through Prolific (www.prolific.co) and the rest (119 participants) were recruited from the Columbia University participant pool. All participants completed an online version of the task hosted on the Gorilla platform (www.gorilla.sc; Anwyl-Irvine et al., 2020). Informed consent was obtained in accordance with the Columbia University Institutional Review Board.

Stimuli

Stimuli were identical to Study 2, except that the 240 images were divided into 2 lists of 120 images each (12 food, 108 non-food images).

Procedure

The procedure was identical to Study 2 with the following exceptions. The experiment consisted of 2 blocks, each of which included a study phase, a distractor phase, and a recall phase (**Figure 1**). In each study phase, participants viewed 120 trial-unique items, which transitioned slowly from one into another. Trial duration was 4s instead of 6s.

The distractor phase was identical to that in Study 2. The recall phase was similar to Study 2, except that participants were given the option to recall for a longer duration. Participants were initially given 4 minutes (broken into 2 recordings of 2 minutes each) to verbally recall items from the study phase. After the initial 4 minutes of recording, participants were given the option of recording for an additional 2 minutes. This was done because the encoding blocks in Study 4 were longer than those in Study 2; thus, we wanted to give participants more time to recall if they needed it.

Analyses

Analyses were identical to Study 2.

Results

Defining attentional states at encoding

In the encoding task, participants viewed images and judged each as being a non-food item (with a button press) or a food item (by withholding their response). Overall, mean response time (RT; defined from image onset) was 2.44s (SD = 0.30). Median RT was 2.47s.

As in Studies 1-3, we performed a variance time course analysis on the encoding phase RTs. **Figure 12A** shows the VTC analysis for one sample participant in Study 4.

The mean length of an “in the zone” segment was 5.10 trials (SD = 0.66) and the mean length of an “out of the zone” segment was 5.08 trials (SD = 0.66; Note that each trial was 4 seconds long). The mean length of a segment did not differ between the two attentional states (t_{123} = 0.95, p = 0.34, Cohen’s dz = 0.09, 95% CI [-0.02, 0.06]). The mean number of fluctuations within a block (i.e., the number of times participants transitioned from one state to another) was 22.87 (SD = 2.90). The number of trials within a segment ranged from 1 to 34 for “in the zone” states and from 1 to 29 for “out of the zone” states, across all blocks and participants.

These attentional states were used to examine accuracy on the encoding task and subsequent recall performance, described below.

More encoding errors during “out of the zone” attentional states

Participants once again performed very well on the encoding task (“Is this item a food or a non-food item?”). They responded to 87.54% (SD = 2.80%) of the “go” non-food image trials, which required a response. Mean accuracy (defined as correct responses on “go” trials and withheld responses on “no-go” trials) was 94.84% (SD = 3.85%).

We next examined errors in the encoding task as a function of attentional state. We replicated Studies 1 and 2 and prior studies (Rosenberg et al., 2011; Esterman et al., 2013). Participants made significantly more errors during an “out of the zone” attentional state (mean ± SD: 7.46 ± 5.89) compared to an “in the zone” attentional state (1.59 ± 2.40; t_{123} = 13.16, p < 0.0001, Cohen’s dz = 1.18, 95% CI [4.99, 6.75], **Figure 12B**). Thus, the VTC analysis was once again successful in identifying fluctuations between better and worse attentional states.

Recall performance is better for items encoded during “in the zone” states

We next examined recall performance. Mean recall (i.e., the total number of items correctly recalled across all blocks) was 39.02 (SD = 17.67); mean recall within a block was 19.51 (SD = 8.84).

We then separately examined recall performance based on whether items were encoded “in the zone” or “out of the zone”. Unlike Studies 1-3, we found a significant difference between the attentional states, such that participants recalled more items that were encoded during an “in the zone” (Mean ± SD: 19.91 ± 9.48) vs. “out of the zone” (18.73 ± 9.29) attentional state (t_{123} = 2.10, p = 0.038, Cohen’s dz = 0.19, 95% CI [0.06, 2.30], **Figure 12C)**. Thus, attentional states at encoding were associated with a difference in both online task performance and subsequent recall performance, with both being superior for “in the zone” states. This suggests that the VTC analysis was successful in identifying better vs worse attentional states.

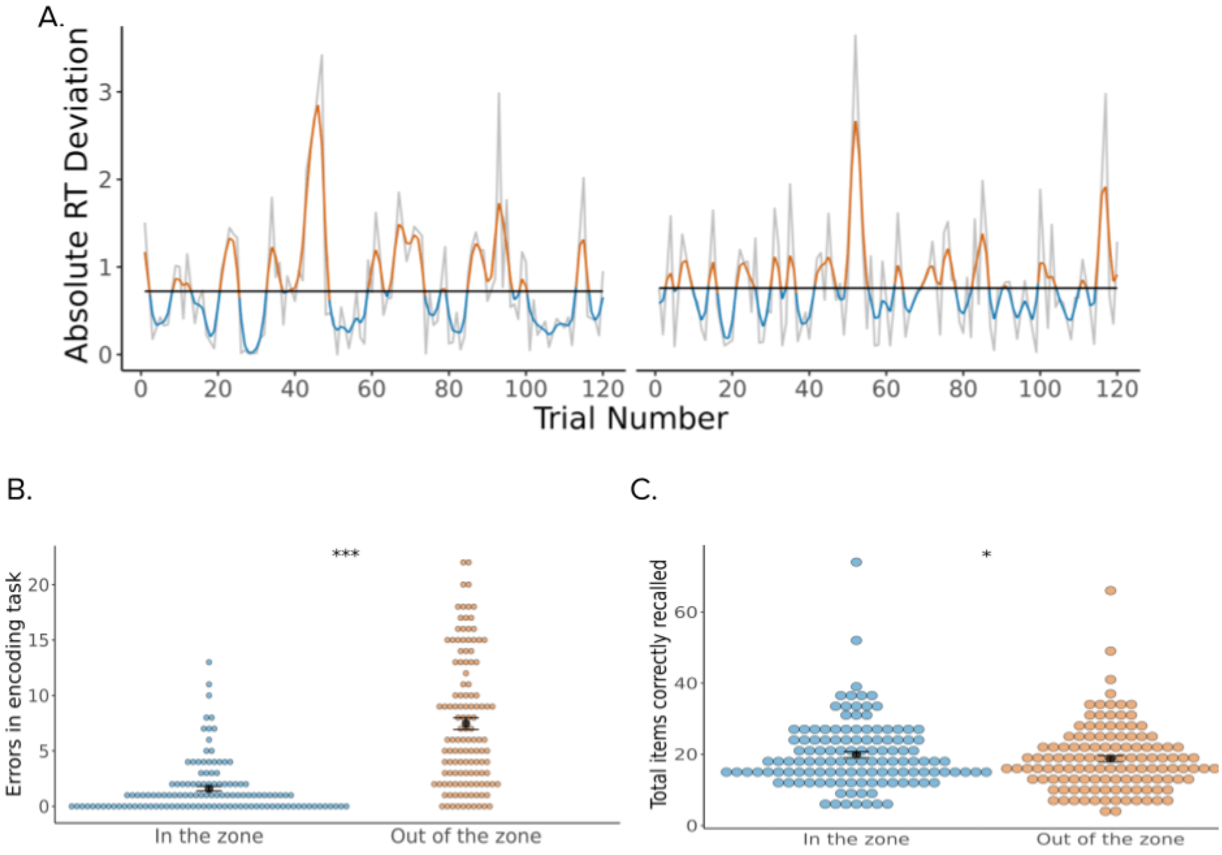

Figure 12. Encoding task performance and recall performance in Study 4. Both encoding errors and recall performance differ between the two attentional states. **A.** Variance Time Course (VTC) analysis for a sample participant, depicting “in the zone” (blue) and “out of the zone” (orange) attentional states. Horizontal black lines indicate the median absolute RT deviation per block. Gray curves indicate raw (unsmoothed) RT deviation per block. **B.** Individual points show the number of encoding judgment errors made by each participant during “in the zone” and “out of the zone” attentional states. Participants made significantly more encoding errors during the “out of the zone” state. **C.** Individual points show the total number of items correctly recalled by each participant as a function of whether items were encoded “in the zone” or “out of the zone”. There was a small but statistically significant difference in recall performance: recall was higher for items encoded while “in the zone” vs “out of the zone”. Black points in panels B & C indicate the mean of the measure with standard error bars. $^{*}p < 0.05$, $^{***}p < .0001$.

No differences in temporal contiguity or forward asymmetry between the two attentional states

As in Studies 1 to 3, we examined lag-CRP curves to explore the temporal organization of recall. This allowed us to determine whether the structure of memory differed between the two attentional states.

Figure 13A shows the overall lag-CRP curve, across participants and blocks, regardless of attentional state at encoding. To test for typical properties of lag-CRP curves, we again conducted a two-way repeated-measures ANOVA on the lag-CRP measures (i.e., lag-conditional recall) with absolute lag (1 to 29) and direction (forward vs. backward) as factors. The Greenhouse-Geisser correction was applied to the absolute lag effects because they violated the assumption of sphericity. We found a significant main effect of absolute lag ($F_{13.44,\ 1653.12} = 7.34$, $p < 0.0001$, $\eta_p^2 = 0.06$): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. There was no main effect of direction ($F_{1,123} = 1.35$, $p = 0.25$ $\eta_p^2 = 0.01$), nor an interaction between absolute lag and direction ($F_{15.96,1963.08} = 1.27$, $p = 0.21$, $\eta_p^2 = 0.01$). However, a paired-samples t-test on the CRP values for +1 and -1 lags revealed a marginally significant difference ($t_{123} = 1.92$, $p = 0.058$, Cohen's dz = 0.17, 95% CI [-0.0003, 0.02]). Thus, we were able to replicate the temporal contiguity effect, but evidence for the forward asymmetry bias was weak (for +1 and -1 lags) or absent (across all lags).

We next tested our primary hypothesis that a good (vs. bad) attentional state at encoding would be related to better temporal organization of subsequent recall. As before, we constructed separate lag-CRP curves for “in the zone” vs. “out of the zone” attentional states based on successive recall of items encoded in the same state (**Figure 13B**). We conducted a three-way repeated-measures ANOVA with attentional state (“in the zone” vs. “out of the zone”), absolute lag (1 to 29), and direction (forward vs. backward) as factors. As before, we expected to find interactions between attentional state and absolute lag and/or direction. Three participants were excluded from this analysis because they did not have any successive recall transitions between items encoded during an “in the zone” attentional state.

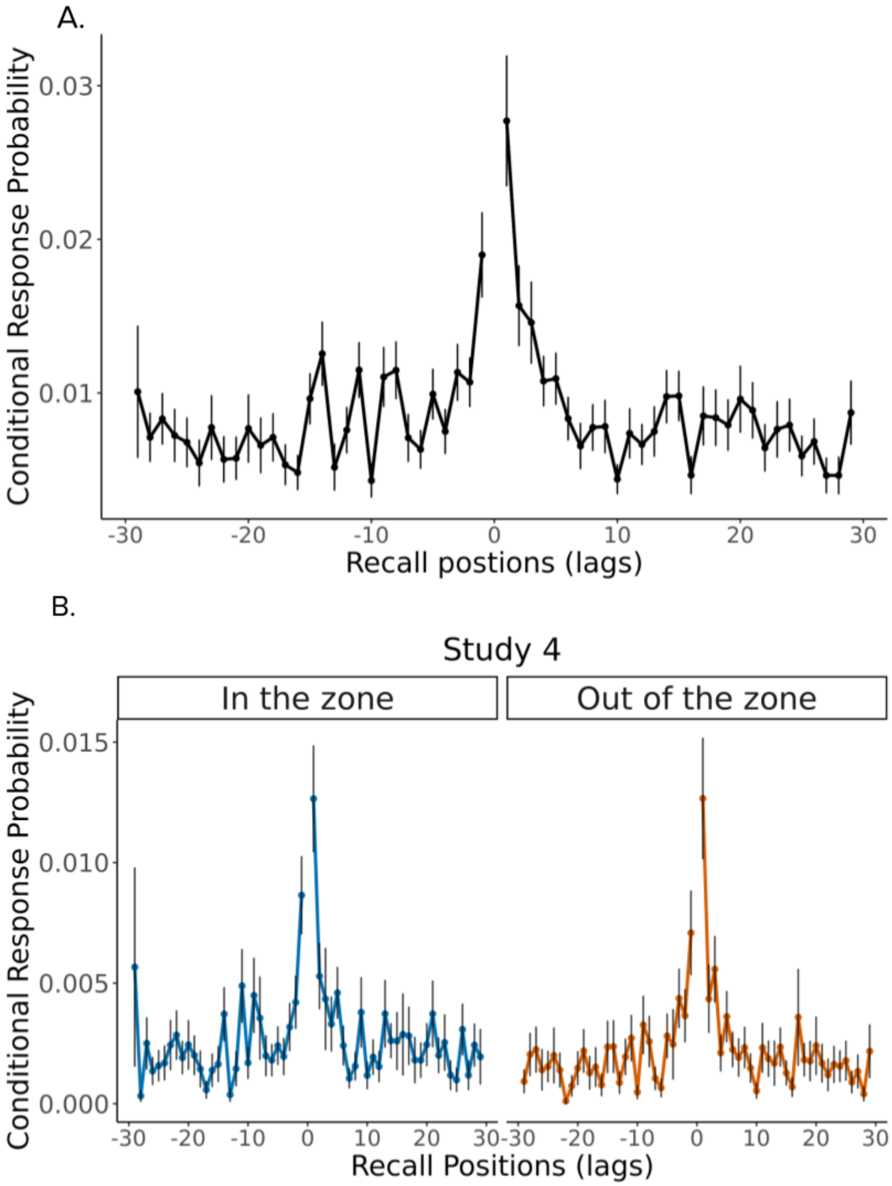

Figure 13. Lag-CRP curves overall and by attentional state for Study 4. **A.** Overall lag-CRP curve across participants and blocks. Individuals were more likely to recall items at nearby lags (main effect of lag), but did not show a bias to recall in the forward direction (no main effect of direction or direction x lag interaction). **B.** Lag-CRP curves plotted separately for items encoded “in the zone” (left) and “out of the zone” (right). There was a main effect of attentional state indicating that participants were more likely to recall items that were encoded during an “in the zone” vs. “out of the zone” attentional state. However, there was no difference between the two attentional states in the temporal organization of recall (neither temporal contiguity nor forward asymmetry). Error bars represent the standard error.

From the three-way repeated-measures ANOVA, we found a significant main effect of absolute lag ($F_{10.64,1276.80} = 9.74$, $p < 0.0001$, $\eta_p^2 = 0.08$): during recall, individuals were more likely to transition to items that were encoded nearby vs. farther away. There was no main effect of direction ($F_{1,120}$ = 2.91, p = 0.09, η_p^2 = 0.02), nor a significant interaction between direction and absolute lag ($F_{13.16,1579.20}$ = 1.50, p = 0.11, η_p^2 = 0.01). Similar to the overall lag-CRP curve results, participants were more likely to recall items at closer vs. farther lags, but this was not significantly different between the forward vs. backward direction. There was a significant main effect of attentional state ($F_{1,120}$ = 4.50, p = 0.036, η_p^2 = 0.04); this reflected higher conditional response probabilities (CRP) for items encoded "in the zone" vs "out of the zone", due to higher overall recall for "in the zone" items. However, contrary to our main hypotheses, there was no interaction between attentional state and direction ($F_{1,120}$ = 0.11, p = 0.74, η_p^2 = 0.001), no interaction between attentional state and absolute lag ($F_{12.04,1444.80}$ = 0.56, p = 0.87, η_p^2 = 0.005), nor a three-way interaction between absolute lag, direction, and attentional state ($F_{13.16,1579.2}$ = 0.85, p = 0.61, η_p^2 = 0.007). Hence, we did not see any differences in recall organization — neither temporal contiguity nor forward asymmetry bias — based on attentional state at encoding.

As before, we also conducted a follow-up analysis to examine differences between the two attentional states at the nearby lags of ± 1. From a two-way repeated-measures ANOVA with lag (+1 vs. -1) and attentional state ("in the zone" vs. "out of the zone") as factors, we found only a significant main effect of lag ($F_{1,120}$ = 5.58, p = 0.02, η_p^2 = 0.04). The main effect of attentional state ($F_{1,120}$ = 0.31, p = 0.58, η_p^2 = 0.003), and the interaction between attentional state and lag, was not statistically significant ($F_{1,120}$ = 0.16, p = 0.69, η_p^2 = 0.001). The significant main effect of lag (+1 vs. -1) confirms that individuals are more likely to make more forward vs. backward transitions at the closest lag (which was marginally significant in the analysis of overall recall performance, reported above, which also included transitions between "in the zone" and "out of the zone" items). Nevertheless, forward asymmetry at the ± 1 lags was not different between the two states. We therefore once again replicated the finding that recall is temporally organized. However, the temporal organization of recall was not different between the two attentional states. This replicates the null findings from the lag-CRP analyses in Studies 1-3. This null effect was observed even though overall recall was higher for items encoded "in the zone" vs "out of the zone".

No differences in event transition types between the two attentional states

We next examined recall transitions as a function of the type of event segment (see **Figure 2** and **Study 1 Methods: Recall Transitions by Event Segment**).

To do this, we performed a two-way repeated-measures ANOVA with transition type (3 levels) and attentional state ("in the zone" vs. "out of the zone") as factors. As before, we hypothesized that "same state, same event" and "same state, different event" transitions may be more likely for items encoded "in the zone" vs. "out of the zone".

We found a main effect of transition type ($F_{2,246} = 25.95$, $p < 0.0001$, $\eta_p^2 = 0.17$). The main effect of attentional state ($F_{1,123} = 0.17$, $p = 0.68$, $\eta_p^2 = 0.001$), and the interaction between attentional state and transition type ($F_{2,246} = 0.43$, $p = 0.65$, $\eta_p^2 = 0.004$), were not statistically significant. This suggests that each type of recall transition is not differentially likely for items encoded "in the zone" and "out of the zone" (**Figure 14**).

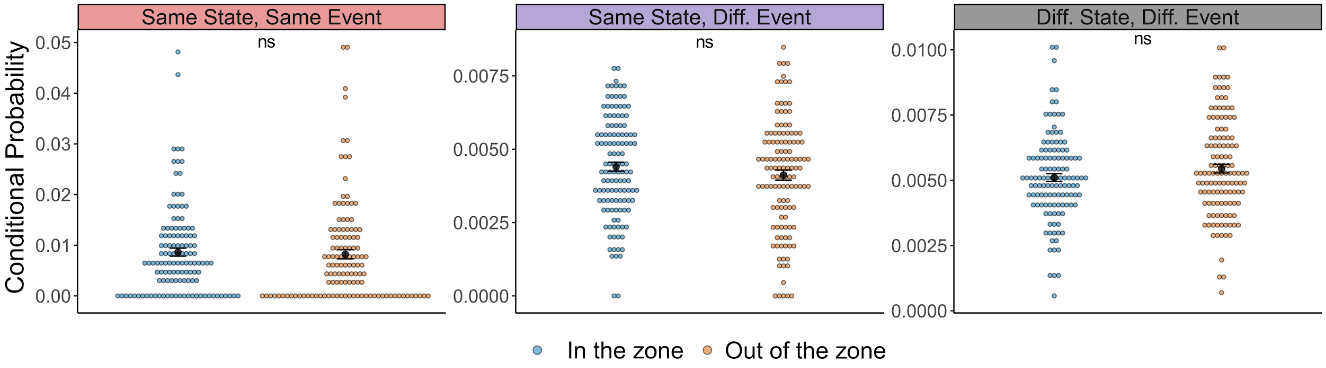

Figure 14. Recall transitions as a function of event type in Study 3. Recall transitions are shown based on whether they occurred within an "event segment' of a particular attentional state (same state, same event), across event segments of a given attentional state (same state, different event), or between attentional states (different state, different event; see **Figure 2).** There were no significant differences in any transition type between the two attentional states. Individual points indicate the conditional probability of each transition type (i.e., the number of times each transition type occurred divided by the number of opportunities to make a transition of that type) for each individual, separately for items encoded "in the zone" and "out of the zone". Black dots indicate the mean with standard error bars. ns = not statistically significant.

We conducted follow-up t-tests to understand the main effect of transition types, collapsing across the two attentional states. As before, we found that "same state, same event" recall transitions were significantly more likely compared to "same state, different event" recall transitions ($t_{123} = 5.83$, $p < 0.0001$, Cohen's dz = 0.52, 95% CI [0.003, 0.006]) and "different state, different event" recall transitions ($t_{123} = 5.43$, $p < 0.0001$, Cohen's dz = 0.49, 95% CI [0.003, 0.006]), However, unlike the prior studies, "different state, different event" transitions were only marginally more likely compared to "same state, different event" transitions ($t_{123} = 1.83$, $p = 0.07$, Cohen's dz = 0.16, 95% CI [-0.00002, 0.0007]).

These results mostly replicate Studies 2 and 3. They are consistent with temporally structured recall because the closest recall transitions are to items in the “same state, same event”. As in Studies 2 and 3, we found no evidence that recall transitions differed between the two attentional states. Thus, although Study 1 showed more “same state, same event” transitions for items encoded “in the zone” vs. “out of the zone”, this effect did not replicate in our subsequent studies and may therefore have been a false positive.

Discussion

In Study 4, we sought to replicate the findings from our prior studies, particularly the lack of a difference in the temporal structure of recall for items encoded “in the zone” vs “out of the zone”. We used a design similar to Study 2 but increased block length and reduced stimulus presentation time to make our design more similar to the traditional gradCPT. As in our other studies, we failed to find any evidence for more temporally structured recall for “in the zone” vs “out of the zone” encoding states.

Interestingly though, this was the first study in which we found an effect of attentional state on subsequent recall. We found a statistically significant difference in recall performance such that participants recalled more items encoded during an “in the zone” attentional state compared to an “out of the zone” attentional state. This was further confirmed by the significant main effect of attentional state from our three-way ANOVA, which showed that the probability of recall was greater for items encoded during an “in the zone” state vs. an “out of the zone” state. Thus, although we found fewer online errors and better overall recall for items encoded “in the zone” vs “out of the zone” (**Figure 12**), and although we replicated temporal contiguity effects in overall recall, we still failed to find evidence for differences across attentional states in recall organization. This suggests that our VTC analysis was able to successfully differentiate between better and worse attentional states, but these states were remarkably similar in the temporal organization of recall. We discuss the implications of our findings and their relation to prior work in the **General Discussion**.

General Discussion

Summary of findings

We examined the behavioral effects of endogenous fluctuations in attention on the temporal organization of memory. We used response time variability at encoding to characterize two attentional states: the relatively good “in the zone” state and the relatively worse “out of the zone” state. We hypothesized that good (vs. bad) attentional states at encoding will be more conducive to maintaining temporal context representations, thus promoting more temporally organized recall and facilitating “leaps” between temporally distant but cognitively similar attentional states. However, across four studies we failed to find consistent evidence to support either hypothesis.

We replicated previous findings that individuals make more errors in online task performance during “out of the zone” states (Rosenberg et al., 2011; Esterman et al., 2013). In Study 4, we also found that recall was worse when encoding occurred in an “out of the zone” state. We also replicated several well-established memory phenomena, including temporal contiguity effects and forward asymmetry in recall (Kahana, 1996; Howard & Kahana, 2002; Healey et al., 2019). Despite this, we found no evidence that the temporal organization of recall was affected by attentional fluctuations at encoding: recall was robustly temporally organized, even when encoding occurred in relatively poor attentional states. Indeed, even when we conducted an analysis that combined Studies 1, 2, and 4 (our diagnostic experiments, in which “out of the zone” attentional states were associated with more online errors), we found no evidence of differential temporal organization of recall as a function of encoding attentional state (all *ps* > 0.34 for interactions involving attentional state). Yet, there was strong evidence for temporally organized recall generally (main effect of lag: $F_{11.48,2858.52} = 32.97$, $p < 0.0001$, $\eta_p^2 = 0.12$; main effect of direction: $F_{1,249} = 6.53$, $p = 0.011$, $\eta_p^2 = 0.03$; lag by direction interaction: $F_{12.6,3137.4} = 2.37$, $p = 0.004$, $\eta_p^2= 0.009$). Together, our findings suggest that temporal context serves as a strong scaffold for episodic memory, one that can overcome spontaneous fluctuations in attentional states. We explore other potential reasons for our findings, their implications, and future directions in the sections below.

Exploring reasons for the null effect of attentional states on recall organization

Why did we not see the hypothesized relationship between attentional states and temporal organization of recall? One possibility is that converting our experiments to online studies increased the noise in our data, hence obscuring any potential effects. However, data from Study 1 suggests this isn’t the case: in control analyses, we found no differences in any measures of interest between online and in-person participants. Furthermore, we replicated established in-lab phenomena in our online-only studies (Studies 2-4) such as the temporal contiguity effect and forward asymmetry in free recall, as well as more errors for “out of the zone” attentional states.

Thus, it is unlikely that moving to online experiments was the main reason behind the lack of evidence supporting our hypothesis.

A second possibility is that measures of RT variability are not sensitive to spontaneous fluctuations in attentional states, and thus, we failed to characterize these states. However, there is strong evidence from sustained attention studies that response time variability effectively captures subtle fluctuations in attentional states, which can then be related to online task performance (e.g., Robertson et al., 1997; Rosenberg et al., 2011; Esterman et al., 2013, 2014). Furthermore, other studies have used RT variability-based attentional states as a trait-level measure and related it to episodic memory (Madore et al., 2020). Our results were consistent with these effects: compared to "in the zone" states, "out of the zone" attentional states were associated with more errors during the encoding task and, in Study 4, worse recall.

Despite the success of the variance time course (VTC) analysis that we used in the current study (Rosenberg et al., 2011; Esterman et al., 2013, 2014; Rosenberg et al., 2015; Madore et al., 2020), there are alternative ways to quantify better vs worse attentional states. For example, some studies have shown that faster (vs slower) RTs are associated with more online errors (Robertson et al., 1997; Cheyne et al., 2006) and worse subsequent recognition memory (deBettencourt et al., 2018; Wakeland-Hart et al., 2021). This can be contrasted to the VTC approach, in which RTs that are too fast *or* too slow are considered to reflect a poor attentional state. To test this alternative characterization, after interpolating RTs on incorrect trials, we performed a median split of RTs to create "worse / faster" vs. "better / slower" attentional states and examined errors that occurred during these states. Consistent with prior work, we found that attentional states linked to faster (vs slower) RTs were associated with more online errors in Studies 1, 2, and 4 (in Study 3, we failed to find a link between attentional states and online errors using both this analysis and the VTC). However, there was no consistent difference in recall organization for attentional states characterized by faster vs slower RTs. Thus, our choice of the VTC analysis over this alternative approach does not change the pattern of results. Nevertheless, other measures of attentional fluctuations, such as pupil diameter changes linked to physiological arousal (Brink et al., 2016; Unsworth et al., 2018; Clewett et al., 2020; Zhang et al., 2020), could be used in future studies to link attentional fluctuations to the temporal organization of recall.

A third possibility is that, in our studies, attentional fluctuations had a more minor effect on recall than other variables did. For example, prior work has shown that list length, presentation times, incidental vs. intentional encoding, emotional salience, and inter-item distraction, among other variables, can influence the temporal organization of recall (Healey et al., 2019; Dester et al., 2020; Gregory et al., 2020; Lazarus et al., 2020; Peris-Yague et al., 2021). Furthermore, recall tests only allow assessment of memories that are sufficiently strong as to be brought to mind without external cues. Approaches that allow us to probe weaker memories may yield different insights. For instance, a study by Schwartz et al. (2005), used a temporally structured recognition memory task to examine the temporal organization of memory. They showed that, when individuals recognized a scene with high confidence, the probability that the next scene would also be recognized with high confidence decreased as the encoding distance between those scenes increased. Thus, future work can index attentional fluctuations during the encoding phase of such a task, and relate these fluctuations to subsequent recognition memory and its sensitivity to the temporal structure of the test. This would allow examination of how attentional fluctuations influence memories that are too weak to be recalled but can nevertheless be recognized. Indeed, other studies have found that attentional fluctuations at encoding influence recognition memory overall (deBettencourt et al., 2018; Wakeland-Hart et al., 2021), leaving open the possibility that such fluctuations also influence the temporal structure of recognition memory.

Relation to prior work

While we did not find evidence supporting our hypothesis that spontaneous fluctuations in attention influence the temporal organization of memory, it is likely that stronger manipulations of attention would affect recall organization. Indeed, there is ample work showing that attention influences memory (see Chun & Turk-Browne, 2007; Aly & Turk-Browne, 2017). Studies involving dual tasks show that divided attention at encoding is associated with worse memory at retrieval (for e.g. Baddeley et al., 1984; Craik et al., 1996; Uncapher & Rugg, 2005). Other tasks involving experimenter-manipulated attention also show robust effects on memory (for example, Yi & Chun, 2005; Uncapher & Rugg, 2009; Aly & Turk-Browne, 2016). One recent study showed that the type of attention at encoding (whether there was a semantic task or no task) influences temporal clustering in recall (Long & Kahana, 2017). Another recent study showed that introducing distractions during encoding disrupts the temporal contiguity effect (Cutler et al., 2020). Thus, explicitly-manipulated attention robustly impacts memory performance generally as well as the temporal organization of recall.

There is evidence that spontaneous attentional fluctuations influence memory, but these studies do not examine the temporal dynamics of recall. One such body of work is research on mind wandering. In these studies, participants are asked to report whether they are “on-task” or “off-task” at various intervals (for example, Smallwood et al., 2003, 2008; Metcalfe & Xu, 2016; Xu & Metcalfe, 2016; Xu et al., 2018; also see Smallwood & Schooler, 2015; & Christoff et al., 2016). These studies have found that more mind-wandering is associated with decreased change detection in memory (Garlitch & Wahlheim, 2020), less precise cued recall (Martarelli & Ovalle-Fresa, 2021), and worse memory performance in general (Smallwood et al., 2003; Risko et al., 2012). Furthermore, as mentioned above, there is evidence that worse attentional states at encoding, as indexed by RTs, are associated with worse recognition memory (deBettencourt et al., 2018; Decker et al., 2020; Wakeland-Hart et al., 2021) and worse associative memory (Elshiekh & Rajah, 2021) in a subsequent test.

Together, the above-reviewed research shows that experimenter manipulations of attention have effects on the temporal structure of recall and that spontaneous attentional fluctuations have effects on other forms of memory. Our current findings suggest that temporal context may be a more powerful driver of memory organization than attentional fluctuations — at least those that occur naturally and spontaneously during a task. Determining the conditions in which spontaneous attentional fluctuations may influence the temporal structure of memory requires further work. Although we did not find evidence for a relationship, future studies using temporally structured recognition tests or other measures of attentional fluctuations (e.g., pupil diameter) will yield important insights.

Conclusion

Across four studies, we did not find any evidence that attentional fluctuations during encoding, as measured with response time variability, influenced the temporal organization of recall. Temporal organization of recall is robust, even for memories encoded during relatively poor attentional states. These findings suggest that temporal context serves as a strong scaffold for episodic memory, one that can overcome spontaneous fluctuations in attentional states. Future research can assess the generality of these results by examining other measures of attention and memory.

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