

Cued Temporal Attention and Episodic Memory

A thesis submitted by

Hunter Johndro

in partial fulfillment of the requirements for the degree of

Master of Science

in

Psychology

Tufts University

May 2019

Advisor: Elizabeth Race, Ph.D.

## Abstract

While the influence of attention to specific locations, objects, and object features on memory is well established, little is known about the mnemonic consequences of attention in another important domain – time. The current experiment explored whether allocating attention toward specific moments in time can modulate memory encoding in both younger and older adults. Temporal attention was manipulated during memory encoding using auditory cues that indicated the temporal onset of visual target items in a speeded response task with 75% validity. Following this, a series of old and new items were shown and participants made a self-paced recognition decision. In both age groups, temporally-predicted items (following valid temporal cues) were responded to faster and remembered better than temporally-unpredicted items (following invalid temporal cues). These results provide novel evidence that allocating attention to specific moments in time influences mnemonic processing across the lifespan.

## Table of Contents

|   |    |
|---|----|
| 1. INTRODUCTION .....   | 1  |
| 2. CURRENT RESEARCH .....                                       | 10 |
| 3. MATERIALS AND METHODS COMMON TO STUDY 1 AND STUDY 2<br>..... | 14 |
| 3.1 Participants .....  | 14 |
| 3.2 Stimuli .....   | 15 |
| 3.3 Procedure .....   | 16 |
| 3.4 Data Processing and Analysis .....                          | 18 |
| 4. STUDY 1 .....  | 19 |
| 4.1 Methods .....   | 19 |
| 4.2 Results .....   | 19 |
| 5. STUDY 2 .....  | 22 |
| 5.1 Methods .....   | 22 |
| 5.2 Results .....   | 23 |
| 6. GENERAL DISCUSSION .....                                     | 26 |
| 7. TABLES AND FIGURES .....                                     | 36 |
| 8. REFERENCES .....   | 40 |

## List of Tables

|  |    |
|--|----|
| Table 1. Mean Reaction Times from the Memory Encoding Task.....          | 36 |
| Table 2. Overall Memory Performance from the Memory Retrieval Task ..... | 36 |
| Table 3. Temporal Cueing Indices from the Memory Encoding Task .....     | 36 |
| Table 4. Temporal Cueing Indices from the Memory Retrieval Task .....    | 36 |

## List of Figures

|  |    |
|--|----|
| Figure 1. Mean RT (s) for trials following Valid and Invalid Temporal Cues in the Temporal Orienting (Memory Encoding) task in Study 1 and Study 2 ..... | 37 |
| Figure 2. Mean Overall Hit Rates for trials following Valid and Invalid Temporal Cues in the Memory Retrieval task in Study 1 and Study 2 .....          | 37 |
| Figure 3. Scatterplot illustrating the correlation between Flanker Congruency Effect and Perceptual Temporal Cueing Index for YA in Study 1 .....        | 38 |
| Figure 4. Scatterplot illustrating the correlation between Flanker Congruency Effect and the Memory Temporal Cueing Index for YA in Study 1 .....        | 38 |
| Figure 5. Scatterplot illustrating the correlation between Flanker Congruency Effect and Perceptual Temporal Cueing Index for OA in Study 2 .....        | 39 |
| Figure 6. Scatterplot illustrating the correlation between Flanker Congruency Effect and the Memory Temporal Cueing Index for OA in Study 2 .....        | 39 |

## Introduction

Anyone who has ever successfully driven home from work only to realize that they cannot recall the details of their commute can appreciate that episodic memory, our memory for specific life events, is dependent on how (and where) we pay attention. There are endless ways that our attention can be focused in any given moment, ranging from attention to internal representations, such as memories, to external representations, such as specific spatial locations or stimulus categories (Chun, Golomb, & Turk-Browne, 2011). But one thing is certain – our attentional capacity is severely limited relative to the vast amount of information in the environment. As a consequence, stimuli that receive our attention are preferentially processed, and memory for these stimuli is enhanced (for a review, see Chun & Turk-Browne, 2007). This comes at a cost, though, in that information that is not attended to is often forgotten (e.g., Yi & Chun, 2005). This is why, for example, the scoring play at a sporting event is less likely to be remembered if you are focused on a different area of the field (irrelevant spatial location), different players (irrelevant object orientation), or the color of the players' jerseys (irrelevant features), rather than the relevant scoring player and their actions themselves.

While the effects of voluntarily orienting attention to specific spatial locations, objects, or features on memory has been a central focus of psychological science for many decades (Chun & Turk-Browne, 2007; Chun et al., 2011), little is known about the impact of attentional orienting in an additional domain – time. The current work aims to investigate whether directing attention

to specific moments in time impacts memory encoding in a manner similar to the effects long observed for spatial-, object-, and feature-based attentional orienting. In addition, it is uncertain if the effects of temporal orienting are preserved with age, and whether those effects extend to higher order cognitive processes in older adults, such as memory, is entirely unknown. It is well established that attentional control declines with age, along with a host of other executive functions, including working memory, inhibitory processing, and other types of controlled processing (Buckner, 2004). However, little is known about age-related changes in attentional control specifically in the temporal domain, or how temporal attention in older adults may influence memory. To that end, the current work also aims to better understand if, and to what degree, temporal orientation is preserved in older adults.

### **The Influence of Attention on Memory**

A robust body of literature clearly describes the impact of attention on learning and memory (Chun & Turk-Browne, 2007). For example, research exploring the consequences of dividing attention during memory encoding has demonstrated that memory is impaired when participants are asked to complete a secondary task. A foundational example of such an observation is that made by Craik, Govoni, Naveh-Benjamin, & Anderson (1996), who asked participants to encode lists of words read out loud while they completed a secondary reaction time (RT) task. This division of attention was associated with sizeable impairments in subsequent memory performance for the words, but little to no differences in sensory processing as measured by the RT task. Similarly, dichotic

listening tasks, in which participants are asked to attend to one of two streams of auditory information presented simultaneously into each ear, result in superior memory for the attended stream and an inability to explicitly remember any information presented in the unattended stream (e.g., Moray, 1959). This latter type of attentional manipulation is an example of top-down *selective attention*, the ability to willfully orient attention toward goal-relevant information in the environment while filtering out goal-irrelevant information.

Though explorations into the influence of selective attention on memory lack in quantity compared to those of divided attention (for reviews see Yonelinas, 2002; Aly & Turk-Browne, 2017), a number of studies manipulating selective attention across several perceptual domains provide consistent evidence for its influence on memory encoding. For example, recent evidence suggests that orienting attention to specific spatial locations in the environment can influence memory encoding (Uncapher, Hutchinson, & Wagner, 2011; Turk-Browne, Golomb, & Chun, 2013). In a study by Uncapher and colleagues (2011), participants were given explicit, symbolic cues (e.g., pointed arrows) indicating the location on a screen where a target could be expected to appear. Participants implicitly encoded targets that appeared at either cued locations (i.e., validly cued trials) or un-cued locations (i.e., invalidly cued trials). When memory was subsequently tested, performance was superior for target items that appeared at cued compared to un-cued or neutral locations. In addition, the authors found that neural activation in regions that play a critical role in memory encoding, such as the medial temporal lobe (MTL), was enhanced for stimuli appearing at cued vs.

un-cued locations. Together, these results demonstrate that expectations provided by spatial cues can direct spatial attention and benefit memory encoding. Similar observations have been made in paradigms asking participants to attend to specific object categories. In a study by Bollinger, Rubens, Zanto, & Gazzaley (2010), participants were given predictive category cues which directed attention to the category of a to-be-encoded stimulus (e.g., a face or scene) or were given neutral category cues, which did not direct attention to a particular stimulus category. In a subsequent long-term memory test, items that followed a predictive category cue were better remembered than items following a neutral cue. Finally, it has long been demonstrated that selectively attending to specific semantic features of a target stimulus results in enhanced memory for the target compared to instances in which attention was directed toward perceptual features of a similar target (“levels-of-processing effect”; Craik & Lockhart, 1972). For example, attending to the meaning of a target word compared to a physical attribute of the word (e.g., whether it appeared in *italics*), has been shown to enhance later memory for that item (Craik & Tulving, 1975). Together, this prior work reveals how orienting attention toward specific spatial, object, and feature information benefits memory encoding.

### **How Does Selective Attention Modulate Memory?**

Two primary mechanisms have been proposed to describe how attentional orienting might influence memory encoding (Aly & Turk-Browne, 2017). The first is based on the influential biased competition model of attentional selection (Desimone, 1998; Desimone & Duncan, 1995) and suggests that attention



influences memory by way of modulating sensory processing. According to this model, visual information in the environment competes for representation in sensory cortices and can be biased for selection by attention-grabbing environmental signals ('bottom-up' attention) or current task demands ('top-down' attention). In the current context, the information selected by an attentional biasing signal is more likely to be transmitted downstream to areas critical for memory encoding (i.e., medial temporal lobes; Aly & Turk-Browne, 2016a, 2016b, 2017; Gazzaley & Nobre, 2012).

A second mechanism was recently proposed by Aly & Turk-Browne (2016a, 2017) and emphasizes a more direct influence of attention on memory encoding that does not depend on enhanced sensory processing. According to their proposal, attention can directly modulate representations of task-relevant information (e.g., stimulus categories) in regions of the brain critical for memory (e.g., hippocampus), which serves to enhance encoding of task-relevant stimuli. Together, these models suggest that attentional orienting may influence memory encoding via multiple mechanisms.

Neural data from several recent studies across different domains of attention provide support for the notion that there are multiple mechanisms by which attention influences memory. For example, when individuals are given cues that indicate the spatial location of an upcoming visual stimulus, activity in frontal, parietal, and visual areas is selectively enhanced for visual targets appearing at the cued location compared to distracting visual stimuli (Kastner, Pinsk, De Weerd, Desimone, & Ungerlieder, 1999). In the study by Uncapher and

colleagues (2011), activity in these same neural regions prior to stimulus presentation was associated with enhanced subsequent memory at a later test of recognition. Similarly, when asked to attend to one of two object categories (faces or scenes), category-specific background connectivity between visual cortex and areas of the MTL (parahippocampal cortex for scenes; perirhinal cortex for faces) was observed (Córdova, Tompary, & Turk-Browne, 2016). In the feature domain, similar enhancement of activity has been observed in feature-specific areas of prefrontal, visual cortex, and medial temporal lobes, which is thought to represent pre-target biasing in these areas for upcoming information, followed by memory encoding (Galli, G. 2014; Geisbrecht, Weissman, Woldorff, & Mangun, 2006; Otten, Henson, & Rugg, 2001). Aly & Turk-Browne (2016a) demonstrated that attention modulates the stability of distributed activity patterns in the hippocampus, with distinct activity patterns for different attentional states (e.g., feature orientations). This representational stability was strongly associated with increased subsequent memory performance, suggesting that attentional signals in the hippocampus influence memory encoding (Aly & Turk-Browne, 2016b, 2017). Taken together, these results suggest that spatial and feature-based attention can modulate memory through multiple mechanisms. An important outstanding question is the extent to which temporal attention can also modulate mnemonic processing.

### **Orienting Attention in Time**

In addition to directing attention to specific spatial locations, features, or objects, attention can also be allocated to specific moments in time when a

meaningful event might occur. One way that attention can be directed to specific moments in time is through the use of symbolic cues that represent specific temporal intervals before the onset of a stimulus (e.g., Cravo, Rohenkohl, Santos, & Nobre, 2017; Samaha, Baur, Cimaroli & Postle, 2015; Coull & Nobre, 1998). Empirical research has demonstrated that this type of top-down attentional cue can optimize information processing at anticipated times by changing the gain or precision of incoming sensory representations, similar to the mechanism described in the biased competition model (Samaha et al., 2015; Rohenkohl, Cravo, Wyart & Nobre, 2012; Schroeder & Lakatos, 2009; Bolger, Coull, & Schön, 2014). Behaviorally, this processing optimization is evident in faster RT and enhanced accuracy in detection, identification, and discrimination of stimuli that appear following valid temporal cues (e.g., Coull & Nobre, 1998; Cravo et al., 2017; Olson and Chun, 2001; Samaha et al., 2015; for review, see Nobre & van Ede, 2018). For example, in a continuous RT task in which participants were given symbolic (auditory) temporal cues, Chauvin, Gillebert, Rohenkohl, Humphreys, and Nobre (2016) found that participants were faster to respond to targets that were shown at predicted intervals (following a valid temporal cue) vs. unpredicted intervals (following an invalid temporal cue). These results suggest that perceptual processing is enhanced when stimuli appear at predictable moments in time and are typically interpreted as evidence for biased sensory processing.

Interestingly, these explicit temporal orienting effects are typically observed when comparing congruent and incongruent trials with a short

foreperiod (i.e., a brief temporal interval between cue and event), but not those with a long foreperiod (i.e., a longer temporal interval between cue and event; Chauvin et al., 2016; Correa, Lupiáñez, Milliken, & Tudela, 2004; Coull & Nobre, 1998). This has been attributed to a reorientation strategy used in the case of long foreperiod trials in which participants conclude that if a stimulus has not yet appeared after a certain amount of time has passed (e.g., the length of a short foreperiod), it should be expected at the later temporal interval (Correra et al., 2004; Triviño, Correa, Arnedo, & Lupiáñez, 2010). The utility of this strategy has been diminished in experiments in which, on occasion, no target is presented to subjects after a temporal cue is provided ('catch trials'; Correra et al., 2004; Triviño et al., 2010). The use of catch trials has been shown to reduce a participant's confidence in a reorientation strategy, as they can no longer presume that a target will appear late if it has not appeared early. For example, in a study by Correra and colleagues (2004), participants completed a temporal-orienting target discrimination task in which targets were cued by either a short-foreperiod cue or long-foreperiod cue. Importantly, in one condition, catch trials (no target) were included, whereas another condition did not contain catch trials. In the catch trial condition only, temporal orienting effects (faster RTs for stimuli following valid vs. invalid temporal cues) were present for both short-foreperiod and long-period cues. These results suggest that catch trials mitigate the effectiveness of a reorientation strategy such that temporal orientation of attention affects perception for both early and late expectancies.

Given that prior research has demonstrated that temporal attention enhances perception, and that enhanced perceptual processing can facilitate memory, this leads to the prediction that temporal attention should also enhance memory. Few studies, however, have investigated the effect of temporal attention on memory, and the results of prior studies investigating this question have been mixed. Initial evidence that temporal regularities might affect memory came from a study by Thavabalasingam, O’Niel, Zeng, and Lee (2016). In this study, participants were presented with target stimuli in either a structured temporal sequence (repeating set of temporal intervals) or an unstructured temporal sequence (non-repeating set of temporal intervals). In a test of subsequent memory, target stimuli presented in the temporally-structured condition were remembered better than those presented in the temporally-unstructured condition. These results suggest that a stable temporal structure of stimulus presentation can convey memory benefits. It is important to note, however, that this type of temporal manipulation differs from the manipulations of temporal attention that have been discussed thus far (i.e., the regularity of target presentation structure itself was manipulated, rather than the voluntary direction of temporal attention). Thus, whether or not explicit temporal cues can similarly benefit memory remains an open question.

The effects of temporal attention on memory have also been investigated in two prior studies that have used *implicit* temporal orienting, as cued by regular background rhythms. The rhythmic structure of background music (e.g., beat or meter) is known to entrain attention such that attention is greatest at predictable

moments aligned with the background rhythm (e.g., in synchrony with the beat or meter; Jones, 1976; Jones & Boltz, 1989). While the effects of such rhythmic temporal cues on perception have been widely demonstrated (e.g., Bolger et al., 2014; Bolger, Trost, & Schön, 2013; Escoffier, Sheng, & Schirmer, 2010; Geiser, Notter, & Gabrieli, 2012; Grahn, 2012), evidence for their effects on memory encoding have been mixed. In one study, Kunert and Jongman (2017) asked participants to perform a continuous RT task for words and non-words shown at moments of higher and lower temporal expectancy in the structure of isochronous auditory rhythms (strong vs. weak beats). As observed in previous research, RTs were faster when responding to targets appearing at strong beats compared to targets appearing at weak beats. However, a subsequent test of recognition memory did not demonstrate a significant effect of temporal expectation on long-term memory performance. In contrast, a more recent study by Johndro, Jacobs, Patel, and Race (2018) presented visual stimuli at moments of higher and lower temporal expectancy (on-the-beat vs. off-the-beat of background, rhythmic music). The authors found that subsequent memory was greater for stimuli presented at temporally-predicted vs. unpredicted moments.

### **The Current Research**

While the prior study by Johndro and colleagues (2018) provided preliminary evidence that implicit temporal cues can influence memory encoding, there are currently no studies that have investigated the extent to which *explicit* temporal orienting can modulate mnemonic processing. As discussed previously,

explicit attentional cues in the spatial, object, and feature domains have been shown to exhibit strong enhancement effects on subsequent memory for valid vs. invalid cues (e.g., Bollinger et al., 2010; Uncapher et al., 2011), and explicit temporal cues have been associated with a variety of behavioral benefits. Study 1 aims to build on prior work investigating attentional orienting in the temporal domain and determine whether explicit temporal cues are able to convey attentional-orienting temporal expectations and, as a consequence, influence memory encoding.

Participants completed a series of three tasks. In the memory encoding task, auditory cues indicated the temporal onset of an upcoming visual target. Three-quarters (75%) of these auditory cues were valid (i.e., the target will appear at the predicted time) while the remaining 25% were invalid (i.e., the target will appear at the unpredicted time). When each target appeared, participants were instructed to make a speeded discrimination response, with the requirement that they place equal emphasis on both speed and accuracy. In the subsequent memory retrieval task, participants were shown a series of old and new items and were instructed to indicate whether they saw each item during encoding. Finally, participants completed an adapted version of the Eriksen Flanker Task (Flanker task; Eriksen & Eriksen, 1974).

At encoding, we predicted that participants' reaction times (RT) would be faster for targets presented after valid, compared to invalid, temporal cues. This result would replicate the finding that explicit temporal cues successfully modulate visual attention (e.g., Chauvin et al., 2016). Due to the use of 'catch'

trials in the present study, we also predicted that the temporal cueing effect would be observed for both short and long-foreperiod trials alike and expected no significant differences in mean RT based on foreperiod length (Corerra et al., 2004; Triviño et al., 2010). Importantly, we predicted that the manipulation of temporal attention at encoding would influence memory encoding, reflected in superior subsequent memory performance for targets presented after valid compared to invalid temporal cues.

Study 2 aims explore whether explicit temporal orienting cues also modulate attention and influence memory encoding in older adults. Although it is well established that attentional processes and executive functioning are compromised with age (e.g., Bollinger et al., 2010; Diamond, 2012; Klein, Ponds, Houx, & Jolles, 1997; Rolle, Anguera, Skinner, Voytek, & Gazzaley, 2017), prior evidence for attentional deficits specifically in the temporal domain have been mixed. In one study by Zanto, Pan, Liu, Bollinger, Nobre, & Gazzaley (2011), older adults did not demonstrate RT facilitation for items presented after a valid temporal cue than those presented after a neutral cue. These results suggest that the effects of temporal orienting observed in younger adults may not be preserved in older adults. However, a more recent study by Chauvin et al. (2016) used a similar paradigm and found that older adults do not differ from younger adults in their ability to attend to particular moments in time. Specifically, both younger and older adults were asked to make a speeded detection response to targets in trials where the duration of the temporal delay before targets were presented was indicated by explicit auditory cues. In both age groups, RTs were faster for trials



preceded by valid temporal cues compared to invalid temporal cues. These results suggest that temporal orienting abilities may indeed be preserved with age, particularly when temporal orienting is measured as the difference in response times to valid compared to invalid temporal cues.

Study 2 aims to replicate and extend the results of Chauvin and colleagues (2016) and investigate (1) whether older adults can use explicit temporal cues to orient attention in time and (2) whether manipulations of temporal attention in older adults modulate memory. Older adult participants completed the same experimental procedure described for Study 1 (see Materials and Methods Common to Study 1 and Study 2) and their performance was compared to the group of younger adults in Study 1. Although we predicted that older adults would generally make slower perceptual decisions and exhibit worse memory performance compared to younger adults, based on results from previous experiments (Chauvin et al., 2016; Triviño et al., 2016) we also predicted that older adults would still be able to use explicit temporal cues to orient attention in time (as measured by faster RTs for valid vs. invalid trials). Importantly, we predicted that temporal orienting would influence memory in older adults in a manner similar to the effect we predicted for younger adults, demonstrated by superior subsequent memory for targets following valid vs. invalid temporal cues. However, these effects in older adults may be related to executive control abilities, such that individuals with higher levels of executive control (as measured by the Flanker task) demonstrate greater effects of temporal orienting on both perception and memory.

## Materials and Methods Common to Study 1 and Study 2

### Participants

Statistical power analysis using G\*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) was performed to determine an estimate of total sample size for Study 1 and Study 2. Input parameters for this analysis included an estimate of effect size  $f$ , a standard  $\alpha$ -error probability (.05), and a highly conservative estimated power ( $1-\beta$ ) of .99. First, the effect size for the temporal orienting effect on perception was estimated. Input parameters were taken from Experiment 2 of Chauvin and colleagues (2016), as this experiment used a similar temporal cuing paradigm in which perceptual reaction time differences were measured in both younger and older adults as a consequence of valid vs. invalid explicit temporal cueing. Chauvin and colleagues (2016) reported significantly faster RTs for validly- vs. invalidly-cued trials in both younger and older adults ( $t(37) = -7.27, p < 0.001$ ). Using these parameters, a power analysis indicated that a total sample size of 16 participants is needed to obtain adequate power for the temporal cueing effect on perception.

Second, the effect size for the anticipated temporal orienting effect on memory was estimated. As there is currently no existing research that has looked at the influence of explicit temporal cues on memory formation, data from a similar study investigating the effect of spatial cues on memory were used (Uncapher et al., 2011). Uncapher and colleagues (2011) reported better memory for validly- vs. invalidly-cued trials ( $t(17) = 5.18, p < 0.0005$ ). Using these

parameters, a power analysis indicated that a total sample size of 15 participants was needed to obtain adequate power for the memory effect.

To obtain adequate power for both the perceptual and memory effects, and to allow for appropriate counterbalancing of the experimental stimuli, 24 younger adults and 24 older adults were recruited for participation. All participants reported normal (or corrected to normal) vision and hearing abilities. Prior to participation, participants provided informed consent in accordance with the Tufts University Institutional Review Board.

### **Stimuli**

**Visual Stimuli.** Visual stimuli consisted of 432 color drawings taken from The Multilingual Picture (MultiPic) databank (Duñabeitia, Crepaldi, Meyer, New, Pliatsikas, Smolka, & Brysbaert, 2017). Items in this database depict common, clearly defined concepts that have been previously standardized for name agreement and visual complexity in several languages. All items included in the current studies were selected for neutral emotional valence and clear category membership for the perceptual discrimination task (see *Procedures Common to Study 1 and Study 2*).

**Auditory Stimuli.** Following the procedures used by Chauvin and colleagues (2016), auditory stimuli used for temporal cueing in both studies consisted of 600 Hz and 1100 Hz tones presented for 150 ms. The 600 Hz tone served as a cue for long-foreperiod trials and the 1100Hz tone cued short-foreperiod trials.

## Procedure

### Temporal Orientation/Memory Task.

**Encoding.** During incidental encoding, participants performed a temporal orienting task adapted from Experiment 2 in Chauvin et al. (2016). During this task, participants initiate each trial with a key press. After a short delay lasting 500 ms (50% probability), 1000 ms (25% probability), or 1500 ms (25% probability), an auditory cue is presented for 150 ms, which indicates the time interval (foreperiod) that should be expected between auditory cue and visual stimulus presentation. In half of the trials, a high pitched auditory cue (1100 Hz) indicated that a short delay (540 ms) will occur before the target was presented, and in the other half of the trials, a low pitched auditory cue (600 Hz) indicated that a long delay (1580 ms) would occur before the target was presented. These cues were valid in 75% of the trials and invalid on 25% of trials. Prior to beginning the task, participants were informed that these auditory cues would help them to predict when each visual target will appear and were asked to utilize the cues throughout the entire task. Upon presentation of the visual targets, participants were instructed to make a semantic decision about the target - "*Is this item living or non-living?*" - while placing equal emphasis on both speed and accuracy.

These instructions and 20 practice trials were given to participants prior to the start of the experiment to familiarize them with the procedure and auditory cues. Participants wore headphones and the volume of auditory cues was kept

constant across participants. Participants then completed 288 trials for visual target discrimination and encoding.

In addition to the trials containing visual targets for encoding, 58 ‘catch’ trials were randomly intermixed among the target trials to eliminate foreperiod effects (Correra et al., 2004), a value equal to 20% of the number of target trials. As in all other encoding trials, catch trials were preceded by high- (50%) and low-pitched (50%) auditory cues, however these trials did not contain a visual target for perceptual discrimination. Participants were alerted to the presence of these trials prior to beginning the task and were instructed to simply rest and wait for the next trial to begin when they occurred.

**Retrieval.** A surprise recognition memory task immediately followed encoding (a delay lasting approximately 5 minutes). Participants were shown all 288 targets from encoding, as well as an additional 144 new items, and asked to make a self-paced recognition (Old/New) decision, as well as a rating of High/Low confidence for each stimulus.

**Stimulus Counterbalancing.** The assignment of the 432 visual targets in the encoding conditions (valid/invalid/catch) and retrieval conditions (target/lures) was counterbalanced across participants. The ordering of cue validity and trial foreperiod was kept constant across participants to control for any effects related to the sequential presentation of same cue validity and foreperiod trial types (Chauvin et al., 2016).

**Flanker Task.** After completing the Temporal Orientation/Memory Task, participants completed an adapted version of the Eriksen Flanker Task (Eriksen &

Eriksen, 1974) as an assessment of executive control abilities. In this task, participants were shown arrays of arrows on a computer screen and instructed to indicate which direction (left/right) the center arrow was pointing with a keypress, placing an equal emphasis on both speed and accuracy. In half of the trials, all arrows in the presented array pointed in the same direction (congruent trials), while the remaining trials consisted of arrays in which the flanking arrows pointed in the opposite direction of the central arrow (incongruent trials). Instructions and 20 practice trials were given to participants to familiarize them with the procedure. The experimental task, which contains 100 trials, was then be completed. Flanker performance is measured as the difference in median RT between incongruent and congruent trials (“congruency effect”).

### **Data Processing and Analyses**

**Memory Encoding.** Accuracy and mean RTs for correct trials were calculated for each condition at encoding. For RTs, individual trials were excluded if they were more than three *SD* from the individual’s mean RT for that condition (Chauvin et al., 2016). The proportion of trials removed for each participant in both Study 1 and Study 2 was low (2%) and did not differ significantly between YA and OA participants. Following Chauvin et al. (2016), a ‘Cueing Index’ was then calculated for each individual by taking the difference between mean RTs in the invalid and valid conditions and dividing by the mean RT in the valid condition. For Study 2, analysis using the Cueing Index ensured

that any age-related effects of cue validity on perceptual performance were not due to a general slowing of RT in OA compared to YA.

**Memory Retrieval.** Hit rates and false alarm rates were calculated to analyze performance on the subsequent memory test. A memory Cueing Index was also calculated for each individual by taking the difference between the mean valid and invalid Hit rates and dividing by the mean Hit rate in the valid condition. For Study 2, analysis using the Cuing Index accounts for potential overall differences in memory performance across age groups.

## Study 1

### Methods

**Participants.** Twenty-four younger adult (YA) participants ( $M_{\text{age}} = 18.9$  years,  $M_{\text{education}} = 12.8$  years, 14 females) were recruited from the Tufts University community and received course credit for their participation. Participants were excluded from analysis if their performance at encoding (accuracy, RT) or retrieval (hit rate) were more than three standard deviations from the group average (Chauvin et al., 2016). This resulted in the exclusion of two YA participants from analysis.

### Results

**Memory Encoding.** Results from the encoding phase of Study 1 are described in Tables 1 & 3 and Figure 1. Accuracy during stimulus encoding was high ( $M = 93.5\%$ ,  $SD = .03$ ). A  $2 \times 2$  ANOVA with cue validity (valid, invalid) and

foreperiod length (short, long) as within-subjects factors indicated that there were no effects of cue validity ( $F(1,21) = 0.57, p = .46, \eta_p^2 = .03$ ) or foreperiod length ( $F(1,21) = 0.25, p = .62, \eta_p^2 = .01$ ) on encoding accuracy. There was also no interaction between cue validity  $\times$  foreperiod length ( $F(1,21) = 1.12, p = .30, \eta_p^2 = .05$ ).

To test whether the temporal cues affected reaction times at encoding, mean RTs were also entered into a  $2 \times 2$  ANOVA with cue validity (valid, invalid) and foreperiod length (short, long) as within-subjects factors. The main effect of cue validity approached significance ( $F(1,21) = 3.92, p = .06, \eta_p^2 = .16$ ). There was not a significant effect of foreperiod length ( $F(1,21) = 2.74, p = .11, \eta_p^2 = .12$ ) nor interaction between cue validity  $\times$  foreperiod length ( $F(1,21) = 0.79, p = .39, \eta_p^2 = .04$ ). We next directly compared performance on the valid and invalid trials using a one-tailed t-test to test the *a priori* hypothesis that participants would respond faster to targets following valid compared to invalid temporal cues. As predicted, participants responded significantly faster to valid, compared to invalidly-cued trials,  $t(21) = -1.98, p = .03, d = -0.42$ , (one-tailed). In addition, though the interaction between cue validity  $\times$  foreperiod length was not significant, we were interested in exploring the manner in which a cueing effect may have presented itself for short or long foreperiod trials, separately. Responses to validly cued items were significantly faster than invalidly cued items for short foreperiod trials,  $t(21) = -2.74, p < .01, d = -0.58$  (one-tailed), but not long foreperiod trials,  $t(21) = -0.95, p = .18, d = -0.20$  (one-tailed).



**Memory Retrieval.** Results from the Memory Retrieval task in Study 1 are described in Tables 2 & 4 and Figure 2. Hit rates were entered into a  $2 \times 2$  ANOVA with cue validity (valid, invalid) and foreperiod length (short, long) as within-subjects factors. There was a main effect of cue validity ( $F(1,21) = 5.41, p = .03, \eta_p^2 = .21$ ), but not foreperiod length ( $F(1,21) = 2.07, p = .17, \eta_p^2 = .09$ ) on memory performance. Direct comparison of valid and invalid trials revealed that this effect was driven by higher hit rates for validly-cued compared to invalidly-cued trials,  $t(21) = 2.33, p = .02, d = 0.50$  (one-tailed; Figure 2). Although there was no interaction between foreperiod length and cue validity ( $F(1,21) = 0.11, p = .74, \eta_p^2 = .00$ ), we were interested in exploring the manner in which a cueing effect may have presented itself for short or long foreperiod trials, separately. For short foreperiod trials, the difference in hit rate for valid vs. invalid trials approached significance,  $t(21) = 1.66, p = .06, d = 0.35$  (one-tailed), and was not significant for long foreperiod trials,  $t(21) = 1.37, p = .09, d = 0.29$  (one-tailed).

**Flanker Correlations.** Cueing Index data for YA in Study 1 can be found in Tables 3 & 4 and Figures 3 & 4. As expected, participants' median RT was faster for congruent trials (mean RT = 0.43 s,  $SD = 0.06$ ) than for incongruent trials (mean RT = 0.49 s,  $SD = .06$ ),  $t(21) = -9.66, p < .001, d = -2.06$ . Spearman rank correlations were performed between Flanker congruency effects (Median  $RT_{\text{Incongruent}} - \text{Median } RT_{\text{Congruent}}$ ) and temporal orienting effects (overall cueing indices) for perceptual performance (using mean RT) and memory performance (using overall Hit Rate). There were no significant correlations between Flanker

congruency effects and the temporal cueing indices for perceptual RT ( $r_s(22) = .09, p = .70$ ) or hit rate ( $r_s(22) = -.22, p = .32$ ).

## Study 2

In Study 1, we replicated the finding that explicit temporal cues can modulate attention (e.g., Chauvin et al., 2016; Zanto et al., 2011), and provided novel evidence that temporal orienting cues can also influence higher-order cognitive processes such as memory. In Study 2, we used the same experimental design to investigate whether these temporal orienting effects are preserved with age.

## Methods

**Participants.** Twenty-four older adult (OA) participants ( $M_{\text{age}} = 73.3$  years,  $M_{\text{education}} = 17.8$  years, 13 females) were recruited from the Tufts University community and received monetary compensation for their participation. Neuropsychological testing for OA participants ( $M_{\text{MoCA}} = 28.1$ ) indicated that two older adults did not meet the minimum score to indicate healthy cognition ( $\geq 26$ ). These participants were excluded from all analyses. In addition, one older adult was excluded based on a low score on the Speech, Spatial, and Qualities of Hearing scale (SSQ; Gatehouse & Noble, 2004;  $M_{\text{SSQ Score}} = 7.71$ , cutoff = 5.57).

As in Study 1, participants were excluded from analysis if their accuracy or RT at encoding or hit rate at retrieval were more than three standard deviations

from their group average (Chauvin et al., 2016). This resulted in the exclusion of two additional OAs and a final sample size of 19 OA.

## Results

**Memory Encoding.** RT data for OA are shown in Tables 1 & 3 and Figure 1. Perceptual accuracy during the memory encoding task was high among OA ( $M = 95.2\%$ ,  $SD = 0.02$ ). Prior to a comparison of RT data, a  $2 \times 2 \times 2$  ANOVA with cue validity (valid, invalid) and foreperiod length (short, long) as within-subjects factors and age (YA, OA) as a between-subjects factor was performed to measure the effects of these factors on accuracy. Results indicated that there was no main effect of cue validity ( $F(1,39) = 0.89$ ,  $p = .35$ ,  $\eta_p^2 = .02$ ) or foreperiod length ( $F(1,39) = 0.49$ ,  $p = .49$ ,  $\eta_p^2 = .01$ ), however, there was a main effect of age, reflecting higher accuracy for OA compared to YA ( $F(1,39) = 4.16$ ,  $p = .05$ ,  $\eta_p^2 = .10$ ). There were no interactions between cue validity  $\times$  foreperiod length ( $F(1,39) = 0.04$ ,  $p = .84$ ,  $\eta_p^2 = .00$ ), cue validity  $\times$  age ( $F(1,39) = 3.22$ ,  $p = .08$ ,  $\eta_p^2 = .08$ ), foreperiod length  $\times$  age ( $F(1,39) = 0.00$ ,  $p = 1.00$ ,  $\eta_p^2 = .00$ ), or cue validity  $\times$  foreperiod length  $\times$  age ( $F(1,39) = 1.90$ ,  $p = .18$ ,  $\eta_p^2 = .05$ ).

A  $2$  (cue validity)  $\times 2$  (foreperiod length)  $\times 2$  (age group) ANOVA was then performed on mean RT at encoding (Figure 3). There was a main effect of cue validity ( $F(1,39) = 4.31$ ,  $p = .04$ ,  $\eta_p^2 = .10$ ), driven by overall faster RT to valid compared to invalidly-cued trials,  $t(40) = -2.13$ ,  $p = .02$ ,  $d = 0.33$  (one-tailed), but no effect of foreperiod length ( $F(1, 39) = 3.66$ ,  $p = .06$ ,  $\eta_p^2 = .08$ ). There was also a main effect of age on mean RT ( $F(1,39) = 57.84$ ,  $p < .01$ ,  $\eta_p^2 =$

.60), reflecting a general slowing in RT for OA compared to YA. There were no interactions between cue validity  $\times$  foreperiod length ( $F(1, 39) = 2.25, p = .14, \eta_p^2 = .05$ ), cue validity  $\times$  age ( $F(1, 39) = 0.14, p = .71, \eta_p^2 = .00$ ), foreperiod length  $\times$  age ( $F(1, 39) = 0.00, p = .97, \eta_p^2 = .00$ ), or cue validity  $\times$  foreperiod length  $\times$  age interaction ( $F(1, 39) = 0.37, p = .55, \eta_p^2 = .01$ ). Although there was not a significant cue validity  $\times$  age interaction, we were interested in whether the cue validity effect was significant in the OA group alone. Responses to valid trials were numerically faster than to invalid trials in OA, but this difference was not significant,  $t(18) = -1.06, p = .15, d = -0.24$  (one-tailed). In addition, though the interaction between cue validity  $\times$  foreperiod length was not significant, we were interested in exploring the manner in which a cueing effect may have presented itself in OA for short or long foreperiod trials, separately. For short foreperiod trials, mean RT differences for valid vs. invalid trials approached significance,  $t(18) = -1.59, p = .06, d = -0.36$  (one-tailed), and were not significant for long foreperiod trials  $t(18) = 0.04, p = .97, d = 0.01$  (one-tailed).

To more specifically test for differences in temporal orienting related to age while accounting for any general slowing of RT, a 2 (foreperiod length)  $\times$  2 (age) mixed ANOVA was performed on the temporal cueing indices for encoding RT. There was not a main effect of foreperiod length ( $F(1,39) = 2.36, p = .13, \eta_p^2 = .06$ ). Importantly, there was also not a main effect of age ( $F(1,39) = 0.61, p = .44, \eta_p^2 = .02$ ) on participants' RT cueing index, indicating that the RT facilitation for valid vs. invalid trials did not differ significantly across age groups. There was also no interaction between foreperiod  $\times$  age ( $F(1, 39) = 0.06, p = .81, \eta_p^2 = .00$ ).

**Memory Retrieval.** Memory data for OA are shown in Tables 2 & 4 and Figure 2. A 2 (cue validity)  $\times$  2 (foreperiod length)  $\times$  2 (age group) ANOVA was run on memory performance (hit rates) at test. There was a main effect of cue validity ( $F(1,39) = 6.68, p = .01, \eta_p^2 = .15$ ), reflecting higher hit rates for valid compared to invalidly cued trials, as well as a main effect of foreperiod length ( $F(1,39) = 4.64, p = .04, \eta_p^2 = .11$ ), reflecting higher hit rates for long compared to short foreperiod trials. There was no effect of age ( $F(1,39) = 0.18, p = .68, \eta_p^2 = .01$ ). Interactions between cue validity  $\times$  foreperiod length ( $F(1,39) = 0.19, p = .67, \eta_p^2 = .01$ ), cue validity  $\times$  age ( $F(1,39) = 0.19, p = .67, \eta_p^2 = .01$ ), and foreperiod length  $\times$  age ( $F(1,39) = 0.02, p = .90, \eta_p^2 = .00$ ) were not significant. The interaction between foreperiod cue validity  $\times$  foreperiod length  $\times$  age ( $F(1,39) = 0.75, p = .39, \eta_p^2 = .02$ ) was also not significant. A direct test of our *a priori* hypothesis that memory performance would be greater for valid compared to invalid trials revealed that although subsequent memory was numerically greater for valid trials compared to invalid within the OA group alone, the main effect of cue validity did not reach significance,  $t(18) = 1.40, p = .09, d = 0.32$  (one-tailed). This result likely reflects substantial variability in the magnitude of the cueing effect in older adults (mean memory cueing effect = .02, SD = .09). In addition, though the interaction between cue validity  $\times$  foreperiod length was not significant, we were interested in exploring the manner in which a cueing effect may have presented itself in OA for short or long foreperiod trials. There difference between mean hit rates for valid vs. invalid trials among OA was not significant for short foreperiod trials,  $t(18) = 0.29, p = .39, d = 0.07$  (one-tailed),

however the same comparison for long foreperiod trials approached significance,  $t(18) = 1.54, p = .07, d = 0.35$  (one-tailed).

To account for any general memory deficits that may arise as a consequence of aging, a 2 (foreperiod length)  $\times$  2 (age) mixed ANOVA was performed on the temporal cueing indices for hit rates. There was no effect of foreperiod length ( $F(1,39) = 0.22, p = .65, \eta_p^2 = .01$ ), and, again, there was not a main effect of age ( $F(1,39) = 0.31, p = .58, \eta_p^2 = .01$ ) on participants' hit rate cueing index. There was also no interaction ( $F(1,39) = 1.32, p = .26, \eta_p^2 = .03$ ). These results suggest that the effect of temporal orienting cues on subsequent memory did not differ across age groups.

**Flanker Correlations.** Cueing Index data for OA in Study 2 can be found in Tables 3 & 4 and Figures 5 & 6. As in Study 1, Study 2 participants' median RT in the Flanker Task was faster for congruent trials (mean RT = 0.58 s,  $SD = 0.062$ ) than for incongruent trials (mean RT = 0.64 s,  $SD = .061$ ;  $t(18) = -8.03, p < .001, d = -1.84$ ). Like in the YA group, there were no significant correlations in the OA group between Flanker congruency effects and the temporal cueing indices for perceptual RT ( $r_s(19) = -.07, p = .79$ ) or overall hit rate ( $r_s(19) = .08, p = .74$ ).

## Discussion

The present pair of studies sought to determine if explicit temporal cues modulate attention and influence subsequent memory performance in healthy younger adults (Study 1) and whether these effects persist throughout the lifespan

(Study 2). In Study 1, faster reaction times (RT) and superior subsequent memory performance were observed among young adult participants (YA) for targets that followed a valid temporal cue compared to an invalid temporal cue. These results replicate prior findings that explicit temporal cues can modulate attention (e.g., Chauvin et al., 2016; Coull & Nobre, 1998; Cravo et al., 2017; Olson & Chun, 2001; Samaha et al., 2015; Zanto et al., 2011; for review, see Nobre & van Ede, 2018) and extend these results to provide novel evidence that explicit temporal cues can also influence higher-order cognitive processes such as memory. In Study 2, the same valid and invalid temporal cues were given to healthy older adults (OA) before the presentation of target items. Though OA had overall slower RTs at encoding and worse memory performance at retrieval compared to YA, OA were still able to benefit from temporal cues, and cuing effects on encoding RT and memory performance did not significantly differ across groups. Together, these results reveal that like attention to specific locations, objects, and object features, allocating attention toward specific moments in time can modulate memory encoding in both younger and older adults.

The main results from the memory encoding tasks in YA largely replicate the perceptual effects observed by both Chauvin et al., (2016) and Zanto et al., (2011). In these studies, YA participants were instructed to react as quickly as possible to the appearance of a target after an explicit temporal cue and reacted faster to targets appearing after a valid, compared to an invalid (or neutral) temporal cue. Notably, Chauvin and colleagues (2016) utilized a similar auditory cueing design, but a more simplified go/no-go perceptual task to demonstrate the

benefits of temporal orienting. Zanto and colleagues (2011) demonstrated similar effects among YA during perceptual detection, discrimination, and go/no-go tasks. In the current study, participants classified targets according to a semantic decision (“Is this item living or non-living?”) to encourage deeper processing of the visual targets so that participants would remember enough targets for a meaningful subsequent memory analysis. However, validity effects for temporal orienting may be task dependent. The use of a more complex task may have reduced the RT benefit observed for valid vs. invalid targets and, indeed, the effect of cue validity on encoding RTs only reached significance when valid and invalid trials were directly compared using a one-tailed t-test. This may also be evidenced by the observation that RTs in the current study, even among YA, are much slower than those observed by Chauvin et al., (2016) and Zanto et al., (2011). Despite this limitation, we note that our primary interest was in the subsequent memory effects, and the presence of an RT effect using these different task parameters does provide additional evidence that the utility of temporal cueing may extend beyond simple RT perceptual decisions (e.g., Corerra et al., 2004; Kingstone, 1992; Kunert & Jongman, 2017).

Additionally, results from the encoding phase in Study 2 demonstrated that OA are able to orient attention in time to a similar degree as YA. These findings inform the prior mixed results for OA in the studies by Chauvin et al., (2016) and Zanto et al., (2011). In the study by Chauvin et al., (2016), RT data were compared for valid vs. invalidly cued trials, and OA were found to utilize these temporal cues, showing a significant RT benefit, in the same manner as YA.



In contrast, Zanto et al., (2011) who compared RT after valid vs. neutral temporal cues showed that YA, but not OA, were able to utilize the temporal cues.

Interestingly, Zanto et al., (2011) noted that OA appeared to perform similarly to YA when the perceptual task involved a simple perceptual decision and motoric response (i.e., detection) as well as a longer time before a response was required (i.e., long foreperiod).

As in the study by Chauvin and colleagues (2016), the validity effect in the current study was measured by comparing valid and invalid trials. While this effect was only observed among YA alone when valid and invalid RTs were compared directly using a one-tailed t-test, it was demonstrated more clearly when RT data were compared without respect to age, and OA demonstrated a validity effect that did not differ significantly from YA. When looking at the OA group alone, however, the effect was no longer significant. As noted previously, and as evidenced by the variability in RT temporal index, this may be related to individual variability among OA in terms of who, and to what degree, temporal cues could be utilized to orient attention in time. Though this variability was not explained by executive functioning as measured by the Flanker task, it could be due to individual differences in other cognitive functions known to change with age, such as temporal processing, working memory, or even language abilities (Coull & Nobre, 1998; Gazzaley & Nobre, 2012). Future studies should test whether the ability of OA to orient attention in time and to use temporal cues to enhance memory encoding depends on these other factors.

In addition to influencing RTs at encoding, the results from Study 1 also provided novel evidence that explicit temporal cues can influence how well information is encoded into long-term memory, resulting in better memory for items following valid vs. invalid temporal cues. Previous efforts to explore the relationship between temporal orienting and mnemonic processing have used implicit forms of temporal cueing (e.g., rhythm - Johndro et al., 2018; Kunert & Jongman, 2017) and have presented mixed results. In the study by Kunert and Jongman (2017), presenting words at moments of higher and lower temporal expectancy throughout an auditory rhythm conveyed a temporal orienting benefit for perceptual processing, but did not result in any mnemonic benefit at a subsequent test of recognition. On the contrary, though the study by Johndro et al., (2018) showed a temporal orienting effect for perceptual, but not semantic decision making, it did demonstrate that subsequent memory was improved for target items presented at predicted compared to unpredicted moments. The current work builds on this previous literature by not only demonstrating both perceptual and mnemonic benefits of temporal orienting within the same group of participants, but does so using explicit temporal cues. Furthermore, these results extend prior work in YA demonstrating the influence of spatial, object, and feature-based attentional orienting on memory to include the temporal domain as well (Bollinger et al., 2010; Bollinger et al., 2011; Córdova et al., 2016; Chun & Turk-Browne, 2007; Chun et al., 2011, Craik et al., 1996; Craik & Lockhart, 1972; Kastner et al., 1999; Turk-Browne et al., 2013; Uncapher et al., 2011).

Notably, validity effects on memory performance among OA in Study 2 did not differ significantly from YA in Study 1. It is well established that attentional processes and aspects of executive functioning, including working memory, are compromised with age (e.g., Bollinger et al., 2010; Diamond, 2012; Klein, et al., 1997; Rolle et al., 2017). These deficits may interact with each other, resulting in broader impairments in the top-down modulation of cognition, and may explain the previously observed inability to form and utilize predictive information, including that in the temporal domain (Bollinger, Rubens, Masangkay, Kalkstein, & Gazzaley, 2011; Zanto et al., 2011; for review see Gazzaley & Nobre, 2012). Indeed, if this were true, executive functioning abilities should correlate with the ability to utilize temporal cues for both perceptual and mnemonic performance, however this was not the case among YA or OA. The current study, then, introduces evidence that suggests that OA may be able to utilize some forms of predictive information (namely, temporal) to benefit memory performance. While previous studies have demonstrated deficits in OA's ability to use predictive cues about upcoming object categories to benefit memory performance relative to YA (Bollinger et al., 2011), temporal cues may be more effective in orienting attention to the benefit of memory, particularly in tasks in which semantic processing is involved.

Again, in both Study 1 and Study 2, participants' Flanker Congruency effects exhibited no significant correlations with temporal cueing indices for perceptual RT or memory performance. These findings indicate that general executive functioning may not be strongly linked to temporal orienting, or, more

likely, that the ability to orient one's attention in the temporal domain does not rely on the same aspects of executive functioning that support performance on the Flanker task, namely conflict monitoring and response inhibition. Though overlap in functional areas supporting spatial and temporal orienting has been observed (Coull & Nobre, 1998), preparing *which* motor movements to make (highly relevant in the Flanker task) and *when* to make them may rely on separate underlying processes. Executive tasks in which temporal preparation is more relevant may better inform the extent to which executive functioning is involved in temporal orienting and the individual differences that may be related to its benefits.

Finally, the current study has produced evidence for the effect of temporal orienting on memory, however the mechanisms supporting this effect remain an open question. Previous literature describes two competing (though not mutually exclusive) models – one in which perceptual processes that feed forward to memory centers are modulated (biased competition; Desimone, 1998; Desimone & Duncan, 1995) and another in which memory processing itself is modulated directly (Aly & Turk-Browne 2016a; 2017). Though the current work cannot distinguish between these possibilities, future work using neuroimaging has the potential to do so. Evidence in the current study that items following valid temporal cues were both responded to faster and remembered better suggests that the temporal cuing effect on memory may be related to the temporal cuing effect on perceptual decision making, as measured by RT. However, there is no association between the magnitude of participants' overall RT cuing benefit (as

measured by the RT cueing index) and participants' mnemonic cueing benefit (as measured by the memory cuing index) ( $r_s(41) = -.09, p = .56$ ), suggesting that the effect of temporal expectations on memory may be distinct from its effect on RT. Indeed, spatial and feature-based attention are known to modulate memory through multiple mechanisms (Aly & Turk-Browne, 2017). Future investigations could address the mechanisms by which temporal attention modulates memory by investigating the degree to which distinct regions of the brain associated with lower-level perceptual processes versus higher-order mnemonic processes (e.g., MTL) are modulated during temporal orienting tasks.

### **Future Directions**

The present work introduces only the first in a series of data points that are needed to better understand the nature of explicit temporal orienting, particularly as it relates to an influence on memory encoding. There are, naturally, additional questions that should be addressed.

First, future studies using electrophysiological (e.g., EEG, ERP) and/or neuroimaging (e.g., fMRI, MEG) tools would be required to better understand the neural mechanisms associated with the temporal orienting effects that were observed in the current research. The use of electrophysiological tools, for example, may provide insight into the manner in which temporal cueing information modulates neural activity during the anticipatory period, prior to the presentation of a target item. It may be useful to couple such findings with the potential results of research that utilizes fMRI, which is capable of measuring

changes in blood flow associated with neural activity in sub-cortical regions including the MTL. Focused observations in this region of the brain may give a clearer picture of how temporal orienting cues may be modulating memory encoding directly, and how this modulation is related to similar types of effects that have been observed in perceptual regions in tasks that used a similar cueing paradigm for object features (Córdova et al., 2016).

In addition, as mentioned previously, executive functioning abilities in the current research did not relate to temporal orienting abilities in a way that was expected, at least to the extent that they were measured by the Flanker task. Future efforts to better understand the role of executive functioning (as well as other individual differences) in temporal orienting tasks may benefit from the use of a secondary task in which temporal perception is more directly involved.

For example, tasks involving either the reproduction or comparison of temporal intervals may be highly suitable. In reproduction tasks, participants are given a target time interval and are instructed to delimit a second time period that corresponds to the target interval, while a comparison task, a participant would be presented with the target interval as well as a secondary interval and would be instructed to indicate whether the second interval was shorter, longer, or identical to the target interval (Zakay & Block, 1997). Performance on such tasks, and temporal perception tasks more generally, has been suggested to rely on the combination of three essential cognitive processes – observing nontemporal properties of the target interval (i.e., perception), the allocation of processing resources to the task and interval stimuli (i.e., attention), and the reference and

comparison against previously established mental representations of the target interval (i.e., memory; Matthews & Meck, 2016).

Performance on both interval reproduction (Broadway & Engle, 2011a) and comparison (Broadway & Engle, 2011b) tasks has been associated with more general executive functioning performance, namely, working memory. In these studies, individuals with higher working memory capacity (WMC) were found to make more accurate and less variable temporal reproductions or comparisons. These results demonstrate that while the aspects of executive functioning that support temporal perception may be limited in number (e.g., to attentional control and working memory), differences in individuals' executive functioning capabilities may be predictive of their temporal orienting abilities. Future research may benefit greatly from using similar tasks to determine if these executive functioning abilities are also related to temporal orienting effects on both perception and memory.

### **Concluding Remarks**

In conclusion, evidence has been gathered that supports our hypothesis that explicit temporal cues modulate attention and influence memory encoding both in younger adults and across the lifespan. This fourth dimension – time - serves an often-overlooked element of our everyday reality, and as research into the nature and effects of temporal perception and expectancy continues to grow, we must be mindful of its constant influence over our thoughts, actions, and intentions.

Table 1  
*Mean Reaction Times from the Memory Encoding Task*

|                   |                    | Study 1 (YA)<br>(n = 22) |               | Study 2 (OA)<br>(n = 19) |               |
|-------------------|--------------------|--------------------------|---------------|--------------------------|---------------|
|                   |                    | <i>Acc.</i>              | <i>RT (s)</i> | <i>Acc.</i>              | <i>RT (s)</i> |
|                   |                    | <i>M (SD)</i>            | <i>M (SD)</i> | <i>M (SD)</i>            | <i>M (SD)</i> |
| <b>Short</b>      | <b>Valid Cue</b>   | .94 (.03)                | 0.61 (.08)    | .96 (.03)                | 0.82 (.10)    |
| <b>Foreperiod</b> | <b>Invalid Cue</b> | .94 (.05)                | 0.63 (.08)    | .95 (.04)                | 0.84 (.12)    |
| <b>Long</b>       | <b>Valid Cue</b>   | .93 (.05)                | 0.62 (.08)    | .96 (.02)                | 0.84 (.09)    |
| <b>Foreperiod</b> | <b>Invalid Cue</b> | .94 (.04)                | 0.63 (.10)    | .94 (.06)                | 0.84 (.10)    |

Table 2  
*Overall Memory Performance from the Memory Retrieval Task*

|                   |                     | Study 1 (YA)<br>(n = 22) |             | Study 2 (OA)<br>(n = 19) |             |
|-------------------|---------------------|--------------------------|-------------|--------------------------|-------------|
|                   |                     | <i>Hit Rate</i>          |             | <i>Hit Rate</i>          |             |
|                   |                     | <i>M</i>                 | <i>(SD)</i> | <i>M</i>                 | <i>(SD)</i> |
| <b>Short</b>      | <b>Valid Cue</b>    | .72                      | (.08)       | .69                      | (.16)       |
| <b>Foreperiod</b> | <b>Invalid Cue</b>  | .69                      | (.14)       | .68                      | (.15)       |
| <b>Long</b>       | <b>Valid Cue</b>    | .74                      | (.09)       | .73                      | (.12)       |
| <b>Foreperiod</b> | <b>Invalid Cue</b>  | .72                      | (.11)       | .69                      | (.15)       |
|                   | <b>False Alarms</b> | .13                      | (.06)       | .27                      | (.17)       |

Table 3  
*Temporal Cueing Indices from the Memory Encoding Task*

|                                | Study 1 (YA)<br>(n = 22) |             | Study 2 (OA)<br>(n = 19) |             |
|--------------------------------|--------------------------|-------------|--------------------------|-------------|
|                                | <i>M</i>                 | <i>(SD)</i> | <i>M</i>                 | <i>(SD)</i> |
| <b>Short Foreperiod Trials</b> | .03                      | (.04)       | .02                      | (.06)       |
| <b>Long Foreperiod Trials</b>  | .01                      | (.06)       | .00                      | (.06)       |
| <b>Overall</b>                 | .02                      | (.04)       | .01                      | (.04)       |

Table 4  
*Temporal Cueing Indices from the Memory Retrieval Task*

|                                | Study 1 (YA)<br>(n = 22) |             | Study 2 (OA)<br>(n = 19) |             |
|--------------------------------|--------------------------|-------------|--------------------------|-------------|
|                                | <i>M</i>                 | <i>(SD)</i> | <i>M</i>                 | <i>(SD)</i> |
| <b>Short Foreperiod Trials</b> | .05                      | (.13)       | .00                      | (.14)       |
| <b>Long Foreperiod Trials</b>  | .03                      | (.11)       | .04                      | (.14)       |
| <b>Overall</b>                 | .04                      | (.08)       | .02                      | (.09)       |



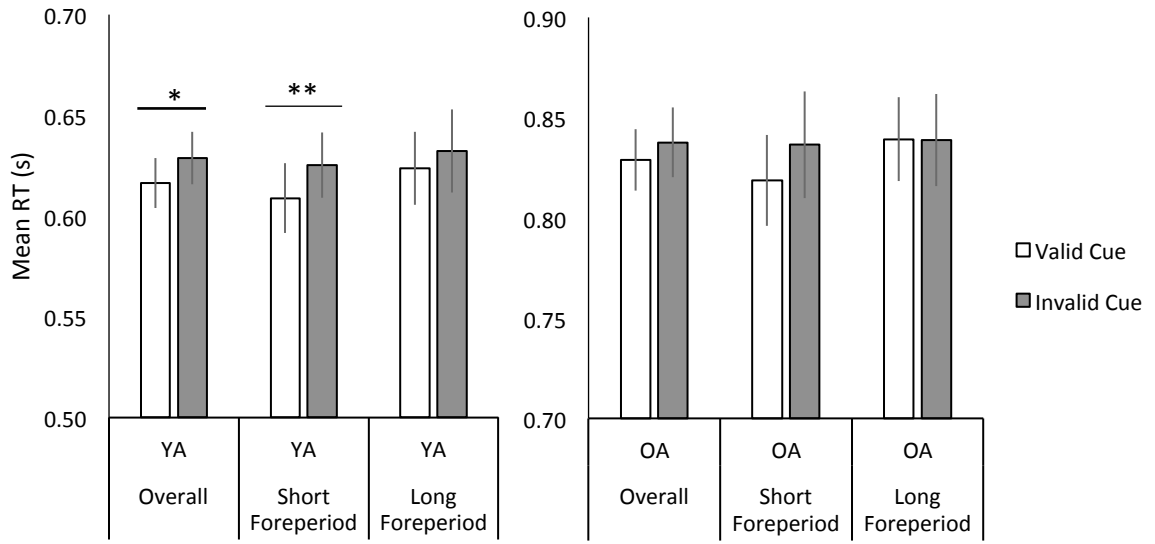


Figure 1 Mean RT (s) for trials following Valid and Invalid Temporal Cues in the Temporal Orienting (Memory Encoding) task in Study 1 and Study 2  
 \*  $p < .05$ ; \*\*  $p < .01$  (one-tailed)

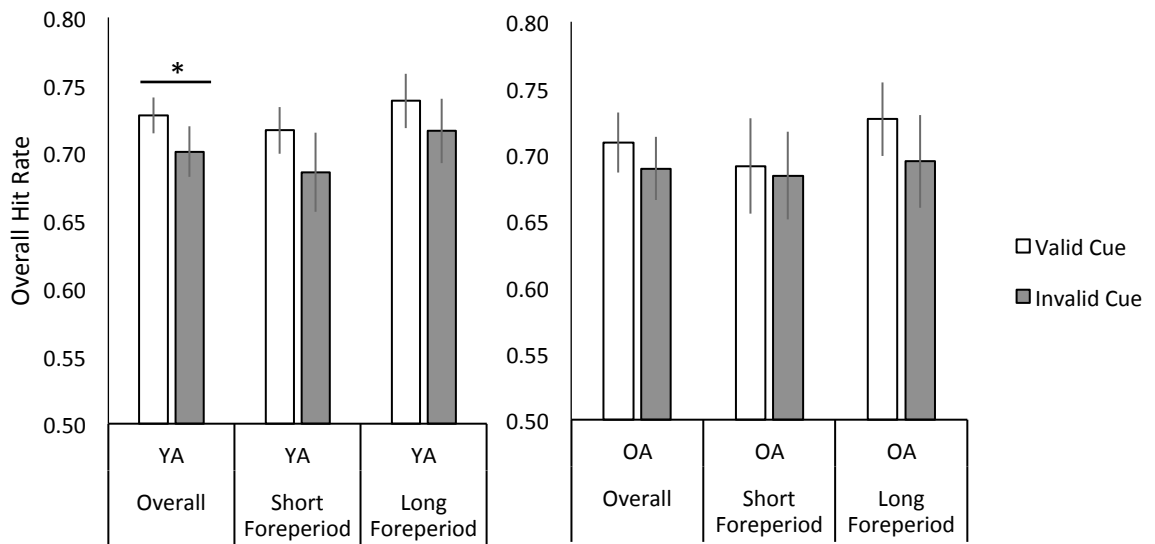


Figure 2 Mean Overall Hit Rates for trials following Valid and Invalid Temporal Cues in the Memory Retrieval task in Study 1 and Study 2  
 \*  $p < .05$

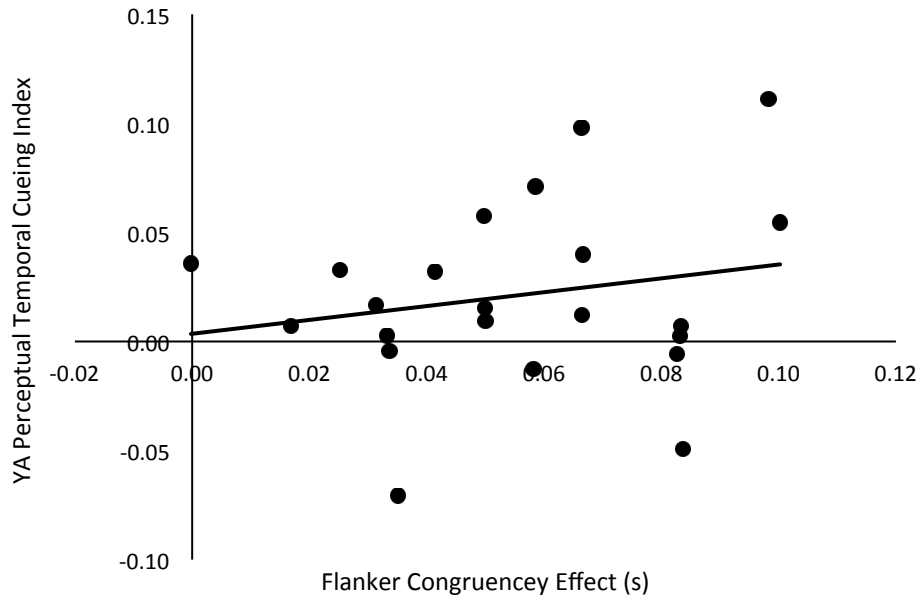


Figure 3 Scatterplot illustrating the correlation between Flanker Congruency Effect and Perceptual Temporal Cueing Index for YA in Study 1

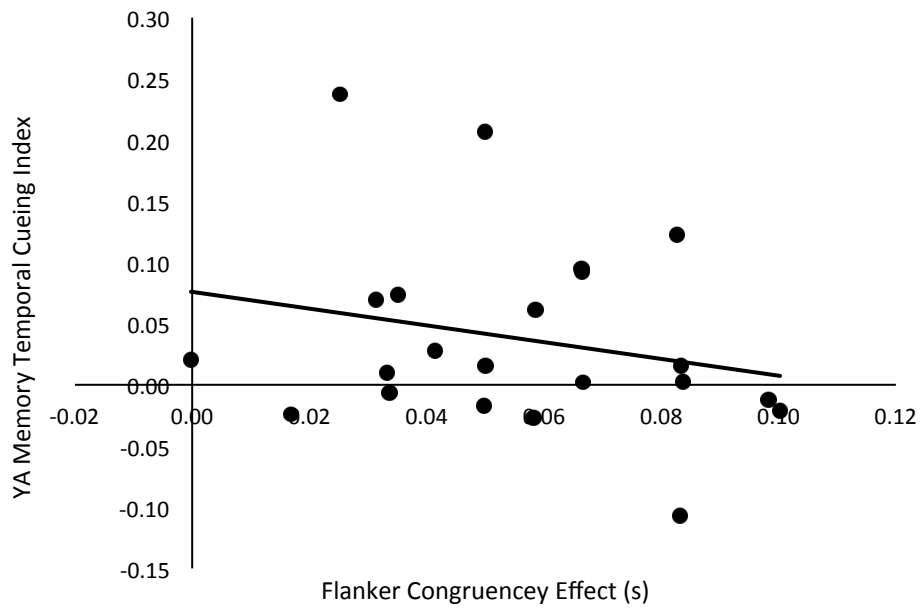


Figure 4 Scatterplot illustrating the correlation between Flanker Congruency Effect and the Memory Temporal Cueing Index for YA in Study 1

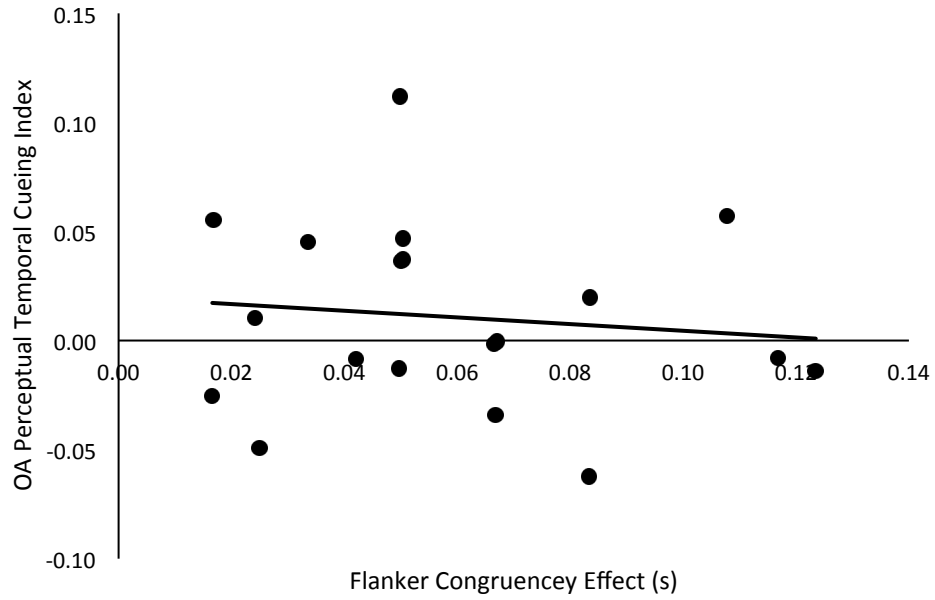


Figure 5 Scatterplot illustrating the correlation between Flanker Congruency Effect and Perceptual Temporal Cueing Index for OA in Study 2

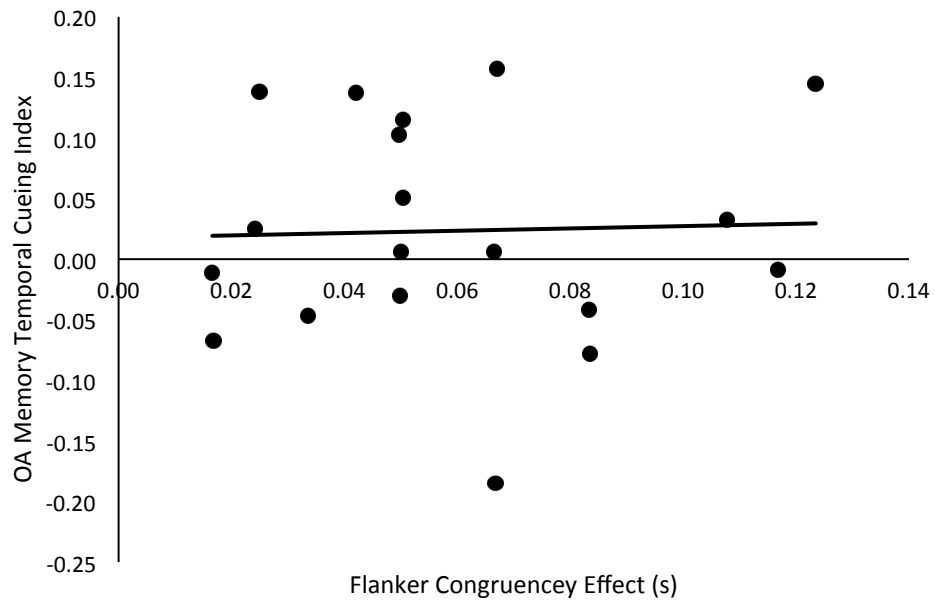


Figure 6 Scatterplot illustrating the correlation between Flanker Congruency Effect and the Memory Temporal Cueing Index for OA in Study 2

### References

- Aly, M., & Turk-Browne, N. B. (2016a). Attention stabilizes representations in the human hippocampus. *Cerebral Cortex*, *26*(2), 783-796.
- Aly, M., & Turk-Browne, N. B. (2016b). Attention promotes episodic encoding by stabilizing hippocampal representations. *Proceedings of the National Academy of Sciences*, *113*(4), E420-E429.
- Aly, M., & Turk-Browne, N. B. (2017). How hippocampal memory shapes, and is shaped by, attention. In *The Hippocampus from Cells to Systems* (pp. 369-403). Springer, Cham.
- Bahrack, L. E., Lickliter, R., & Flom, R. (2004). Intersensory redundancy guides the development of selective attention, perception, and cognition in infancy. *Current Directions in Psychological Science*, *13*(3), 99-102.
- Bolger, D., Coull, J. T., & Schön, D. (2014). Metrical rhythm implicitly orients attention in time as indexed by improved target detection and left inferior parietal activation. *Journal of Cognitive Neuroscience*, *26*(3), 593-605.
- Bolger, D., Trost, W., & Schön, D. (2013). Rhythm implicitly affects temporal orienting of attention across modalities. *Acta Psychologica*, *142*(2), 238-244.
- Bollinger, J., Rubens, M. T., Masangkay, E., Kalkstein, J., & Gazzaley, A. (2011). An expectation-based memory deficit in aging. *Neuropsychologia*, *49*(6), 1466-1475.
- Bollinger, J., Rubens, M. T., Zanto, T. P., & Gazzaley, A. (2010). Expectation-driven changes in cortical functional connectivity influence working memory and long-term memory performance. *Journal of Neuroscience*, *30*(43), 14399-14410.
- Buckner, R. L. (2004). Memory and executive function in aging and AD: multiple factors that cause decline and reserve factors that compensate. *Neuron*, *44*(1), 195-208.
- Broadway, J. M., & Engle, R. W. (2011a). Lapsed attention to elapsed time? Individual differences in working memory capacity and temporal reproduction. *Acta Psychologica*, *137*(1), 115-126.
- Broadway, J. M., & Engle, R. W. (2011b). Individual differences in working memory capacity and temporal discrimination. *PLoS One*, *6*(10), e25422.
- Chauvin, J. J., Gillebert, C. R., Rohenkohl, G., Humphreys, G. W., & Nobre, A. C. (2016). Temporal orienting of attention can be preserved in normal aging. *Psychology and Aging*, *31*(5), 442.
- Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, *62*, 73-101.
- Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology*, *17*(2), 177-184.
- Córdova, N. I., Tompary, A., & Turk-Browne, N. B. (2016). Attentional modulation of background connectivity between ventral visual cortex and the medial temporal lobe. *Neurobiology of Learning and Memory*, *134*, 115-122.

- Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience*, *18*(18), 7426-7435.
- Correa, Á., Lupiáñez, J., Milliken, B., & Tudela, P. (2004). Endogenous temporal orienting of attention in detection and discrimination tasks. *Perception & Psychophysics*, *66*(2), 264-278.
- Craik, F. I., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General*, *125*(2), 159.
- Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*(6), 671-684.
- Craik, F. I., & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General*, *104*(3), 268.
- Cravo, A. M., Rohenkohl, G., Santos, K. M., & Nobre, A. C. (2017). Temporal anticipation based on memory. *Journal of Cognitive Neuroscience*, *29*(12), 2081-2089.
- Desimone, R. (1998). Visual attention mediated by biased competition in extrastriate visual cortex. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *353*(1373), 1245-1255.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*(1), 193-222.
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135-168.
- Duñabeitia, J. A., Crepaldi, D., Meyer, A. S., New, B., Pliatsikas, C., Smolka, E., & Brysbaert, M. (2017). MultiPic: A standardized set of 750 drawings with norms for six European languages. *The Quarterly Journal of Experimental Psychology*, (just-accepted), 1-24.
- Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143-149.
- Escoffier, N., Sheng, D. Y. J., & Schirmer, A. (2010). Unattended musical beats enhance visual processing. *Acta Psychologica*, *135*(1), 12-16.
- Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G\* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175-191.
- Galli, G. (2014). What makes deeply encoded items memorable? Insights into the levels of processing framework from neuroimaging and neuromodulation. *Frontiers in Psychiatry*, *5*, 61.
- Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: bridging selective attention and working memory. *Trends in Cognitive Sciences*, *16*(2), 129-135.

- Geiser, E., Notter, M., & Gabrieli, J. D. (2012). A corticostriatal neural system enhances auditory perception through temporal context processing. *Journal of Neuroscience*, *32*(18), 6177-6182.
- Giesbrecht, B., Weissman, D. H., Woldorff, M. G., & Mangun, G. R. (2006). Pre-target activity in visual cortex predicts behavioral performance on spatial and feature attention tasks. *Brain Research*, *1080*(1), 63-72.
- Grahn, J. A. (2012). See what I hear? Beat perception in auditory and visual rhythms. *Experimental Brain Research*, *220*(1), 51-61.
- Johndro, H., Jacobs, L., Patel, A., & Race, E. (2018). *Rhythmic enhancement of visual long-term memory*. Manuscript in preparation.
- Jones, M. R. (1976). Time, our lost dimension: toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323.
- Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*(3), 459.
- Kastner, S., Pinsk, M. A., De Weerd, P., Desimone, R., & Ungerleider, L. G. (1999). Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron*, *22*(4), 751-761.
- Klein, M., Ponds, R. W., Houx, P. J., & Jolles, J. (1997). Effect of test duration on age-related differences in Stroop interference. *Journal of Clinical and Experimental Neuropsychology*, *19*(1), 77-82.
- Kunert, R., & Jongman, S. R. (2017). Entrainment to an auditory signal: Is attention involved?. *Journal of Experimental Psychology: General*, *146*(1), 77.
- Lewkowicz, D. J., & Hansen-Tift, A. M. (2012). Infants deploy selective attention to the mouth of a talking face when learning speech. *Proceedings of the National Academy of Sciences*, *109*(5), 1431-1436.
- Matthews, W. J., & Meck, W. H. (2016). Temporal cognition: Connecting subjective time to perception, attention, and memory. *Psychological Bulletin*, *142*(8), 865.
- Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, *11*(1), 56-60.
- Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., ... & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695-699.
- Nobre, A. C., & van Ede, F. (2018). Anticipated moments: temporal structure in attention. *Nature Reviews Neuroscience*, *19*(1), 34.
- Olson, I. R., & Chun, M. M. (2001). Temporal contextual cuing of visual attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(5), 1299.
- Otten, L. J., Henson, R. N., & Rugg, M. D. (2001). Depth of processing effects on neural correlates of memory encoding: relationship between findings from across-and within-task comparisons. *Brain*, *124*(2), 399-412.

- Rohenkohl, G., Cravo, A. M., Wyart, V., & Nobre, A. C. (2012). Temporal expectation improves the quality of sensory information. *Journal of Neuroscience*, *32*(24), 8424-8428.
- Rolle, C. E., Anguera, J. A., Skinner, S. N., Voytek, B., & Gazzaley, A. (2017). Enhancing Spatial Attention and Working Memory in Younger and Older Adults. *Journal of Cognitive Neuroscience*, *29*(9), 1483-1497.
- Samaha, J., Bauer, P., Cimaroli, S., & Postle, B. R. (2015). Top-down control of the phase of alpha-band oscillations as a mechanism for temporal prediction. *Proceedings of the National Academy of Sciences*, *112*(27), 8439-8444.
- Schroeder, C. E., & Lakatos, P. (2009). Low-frequency neuronal oscillations as instruments of sensory selection. *Trends in Neurosciences*, *32*(1), 9-18.
- Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior research methods, instruments, & computers*, *31*(1), 137-149.
- Thavabalasingam, S., O'Neil, E. B., Zeng, Z., & Lee, A. C. (2016). Recognition memory is improved by a structured temporal framework during encoding. *Frontiers in Psychology*, *6*, 2062.
- Triviño, M., Correa, Á., Arnedo, M., & Lupiáñez, J. (2010). Temporal orienting deficit after prefrontal damage. *Brain*, *133*(4), 1173-1185.
- Turk-Browne, N. B., Golomb, J. D., & Chun, M. M. (2013). Complementary attentional components of successful memory encoding. *NeuroImage*, *66*, 553-562.
- Uncapher, M. R., Hutchinson, J. B., & Wagner, A. D. (2011). Dissociable effects of top-down and bottom-up attention during episodic encoding. *Journal of Neuroscience*, *31*(35), 12613-12628.
- Yi, D. J., & Chun, M. M. (2005). Attentional modulation of learning-related repetition attenuation effects in human parahippocampal cortex. *Journal of Neuroscience*, *25*(14), 3593-3600.
- Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language*, *46*(3), 441-517.
- Zanto, T. P., Pan, P., Liu, H., Bollinger, J., Nobre, A. C., & Gazzaley, A. (2011). Age-related changes in orienting attention in time. *Journal of Neuroscience*, *31*(35), 12461-12470.
- Zakay, D., & Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science*, *6*(1), 12-16.