

INVESTIGATION OF TEMPORAL EXPECTANCY, MEMORABILITY AND
SUBJECTIVE DURATION

by

Ayana Cameron
A Thesis
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Master of Arts
Psychology

Committee:

_____ Director

_____ Department Chairperson

_____ Dean, College of Humanities
and Social Sciences

Date: _____ Spring Semester 2021
George Mason University
Fairfax, VA

Investigation of Temporal Expectancy, Memorability and Subjective Duration

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts at George Mason University

by

Ayana Cameron
Bachelor of Science
United States Air Force Academy, 2014

Director: Martin Wiener, Assistant Professor
George Mason University

Spring Semester 2021
George Mason University
Fairfax, VA

Copyright 2018 Ayana Cameron
All Rights Reserved

ACKNOWLEDGEMENTS

I would like to give a special thanks to Dr. Martin Wiener, Keri Gladhill, Farah Bader, Candice Stanfield-Wiswell and Colleen Garrity for all their help in pursuing this degree. I could not have asked for a better lab to be a part of! I would also like to thank my family for their support and encouragement through the late nights and early mornings. Finally, thank you to the Air Force Institution of Technology for giving me the opportunity to accomplish this while fulfilling my service to the country. The views expressed in this article are those of my own and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

TABLE OF CONTENTS

	Page
List of Tables	v
List of Figures	vi
Abstract	vii
Introduction	1
How Expectation Influences Time Perception	3
Measuring Memorability	6
Current Research: Where do Time, Memory, and Expectation Collide?	10
Method for Both Experiment 1 and Experiment 2	12
Participants	12
Materials	12
Experiment 1: Perceived Duration and Memorability	14
Stimuli	14
Task	15
Data Analysis	16
Results	16
Experiment 2: Temporal Expectancy and Memorability	20
Stimuli	20
Task	20
Data Analysis	24
Results	24
Discussion	28
References	34

LIST OF TABLES

Table	Page
Table 1 Simple Main Effects of Memorability on Duration.....	18
Table 2 Post Hoc Analysis with Holm Correction of p on Memorability Bin	26

LIST OF FIGURES

Figure	Page
Figure 1 Psychometric Graph of $p(\text{long})$ by Duration for Each Memorability Bin with Standard Error Bars.....	17
Figure 2 Mean Reaction Time (RT) for Each Duration by Memorability Bin with Standard Error Bars.....	19
Figure 3 Repeated Measures ANOVA on Accuracy with Memorability as Main factor with Standard Error Bars	26
Figure 4 Main Effect of Memorability on d' (plot A) and C (plot B) with Standard Error Bars	27

ABSTRACT

INVESTIGATION OF TEMPORAL EXPECTANCY, MEMORABILITY AND SUBJECTIVE DURATION

Ayana Cameron, M.A.

George Mason University, 2021

Thesis Director: Dr. Martin Wiener

The current study examines the interaction between time and memory, specifically how a rhythmically structured context influences the memorability of visual stimuli and whether memorability of an image modulates perceived duration. This was achieved through a multi-part study split into two behavioral experiments, the first of which uses a temporal bisection task to evaluate whether images with varying levels of memorability modify how long they are perceived to appear for. Using the same images, the second experiment utilizes a recognition memory test paradigm to measure whether temporal expectancy can improve memory performance. Previous research on time and memory shows that rhythmic priming created through temporal expectancy enhances visual recognition processing and that the memorability of an image is measurable and predictable based on certain properties (such as atypicality or valence). The results of my research support these ideas, as I found that participants perceived images with higher

memorability scores as appearing for longer durations. Additionally, despite memorability, images encoded in a structured temporal context resulted in higher accuracy and better recognition memory performance. An expansion of these findings in future research will help us understand the cognitive processes behind these phenomena and how they might interact and be manipulated to modulate time perception and memory.

INTRODUCTION

The study of time and how we perceive it has been investigated through many lenses, from the complex behaviors it informs to the underlying neural mechanisms that drive it. The research at hand, however, is particularly interested in examining the subjective nature of perceived duration and how sensitive it is not only to the visual world, but our memories of it. Over the course of more than three decades, several diverging fields of thought have emerged to shape the question surrounding time perception. In their paper, Ivry and Schlerf (2008) distil them into two main models – intrinsic and modular. Theories with an intrinsic model perspective suggest that timing is an innate aspect of neural dynamics, and thus it is sensitive to specific contexts and modalities. In contrast the modular, or dedicated, model suggest there is a central timing mechanism for specific neural regions. One of the most utilized modular models is the scalar expectancy theory (SET), also referred to as the pacemaker-accumulator model (Gibbon et al., 1984). In SET, there are three components of temporal information processing – the internal clock (or pace-maker) which creates pulses as a mechanism to measure duration, the storage of the accumulated pulses (representative of duration) into reference memory then the subsequent retrieval of these pulses to compare them to the pulses in working memory, and finally the decision process that leads to a subjective time judgment.

Notably, several studies that provide convincing evidence for SET reveal two consistent factors, attention and arousal, that appear to affect distinct aspects of the model (Gil and Droit-Volet, 2012; Droit-Volet et al., 2011; Ogden et al., 2015; Ogden et al., 2019; Zakay and Block, 1997). Specifically, when arousal and attention are heightened, studies typically show an overestimate in time assumed to be because the pace-maker is increasing pulses and the accumulation of those pulses is occurring (respectively). In the opposite situation, however, low arousal produces less pulses and reduced attention to time stops accumulation of those pulses which results in an underestimation of time.

Modular models, such as SET, have been used by many temporal perception studies to better understand how and why certain visual properties modulate subjective duration. For example, there is evidence correlating underestimations of time with luminance and saccadic eye movement (Ayhan et al., 2011; Morrone et al., 2005) and overestimations of time with stimuli that are unexpected, symmetrical, or that appear in crowded and normal scene structures as opposed to uncrowded or scrambled scenes (Ogden et al., 2016; Palumbo et al., 2015; Shimokawa and Sugimori, 2019; Tse et al., 2004; Varakin et al., 2013). Still, there is growing evidence that the effects of many visual properties, such as stimulus complexity and emotion, modulate subjective duration bidirectionally depending on their semantic context and temporal expectancy (Droit-Volet and Meck, 2007; Folta-Schoofs et al., 2014; Palumbo et al., 2014). While some researchers claim this gives credence to the intrinsic model of temporal processing – suggesting judgment durations rely on the sensitivity of specific “temporal contingencies” of neural processing (Ayhan et al., 2011; Johnston and Nishida, 2001) – I

suggest instead that it underscores the complex relationships between the phases of SET. For example, in terms of emotion, an overestimation of duration is seen for negative emotional stimuli when compared to neutral stimuli, but this effect is reversed if the emotional stimuli become distractors, rather than targets (Lake et al., 2016; Gladhill et al., 2020; Lui et al., 2011). Notably, Dirnberger and colleagues (2012) also found that emotional stimuli that were perceived as lasting longer were also remembered better. This suggests that emotional stimuli not only affect arousal, but that the inherently nature of that arousal influences encoding strength and memory of those stimuli, and thus the perceived timing of its presentation.

How Expectation Influences Time Perception

This idea of modulating the attentional effect of a stimulus through temporal expectancy is not new. Several studies conducted by Boltz (1989;1993) on the influence of various types of temporal expectancies show that the type of temporal contrast, defined as a momentary surprise that represents a difference between expected and observed endings, created by a violation to temporal expectancy significantly influenced how duration was perceived. Specifically, positive contrast (created by an event later than expected) led to overestimates while negative contrasts (created by an event ending earlier than expected) tend to create underestimates of time (Boltz, 1993). Boltz's results provide evidence supporting a major assumption of the contrast model, that estimates are significantly influenced by the structure of their context (Boltz, 1989). Additionally, Zakay and Block (1997) later expanded this in their contextual-change hypothesis which suggest that while these results are likely due to the retrospective nature of Boltz's

experiments, the context in which a stimulus is experienced nonetheless influences how it is remembered and subsequently judged in terms of duration.

Research today continues to underline the benefit of temporal expectancy on memory, and many studies are pointing to changes in sensory processing as the underlying cause. One study by Rohenkohl and colleagues (2012) used an orientation discrimination task to investigate the role of temporal expectancy on information processing. In their paradigm, subjects had to discriminate between circular Gabor patches tilted either + or -45° that appeared in seven levels of contrast sensitivity that were calibrated for each participant. To create temporal expectancy, they manipulated the stimulus-onset asynchrony (SOA) with fixed durations for the regular trials (400 ms) and jittered durations for the irregular trials (200, 300, 400, 500, 600 ms). At the conclusion of the study they found that subjects had higher discrimination for targets that appeared in the regular condition. Additionally, they also saw a significant effect of reaction times (RTs), finding RTs were shorter with higher contrast stimuli in the regular condition versus the irregular condition. Increased RTs for temporally structured context seems to be consistent across multiple studies. Interestingly they provide evidence that the signal-to-noise accumulation rate, k , correlated significantly with effect of temporal expectation on the speed and performance. These findings support the idea that temporally structured contexts entrain attentional focus which modulates the subsequent processing of relevant information (Rohenkohl et al., 2012).

Thavabalasingam and colleagues (2015) take this a step further in their study and suggest that temporal expectancy not only enhances early visual areas but higher-level

cognitive processes like memory. In their trilogy of experiments, subjects take a repeated measures recognition memory test using real world, gray scale pictures. The memory test was split into a test phase, where they are shown 48 novel images, and a study phase where they are shown a mix of new and old images and asked to distinguish between the two. Each participant completed the task in a temporally structured and temporally unstructured condition. Similar to Rohenkohl and colleagues (2012), they used fixed and jittered intervals to create the temporal conditions, however, their intervals differ in two important ways: first, they used inter-stimulus intervals (ISIs) and secondly, they used a set of “fixed” intervals (100, 500, 1000, and 2000 ms) to create random but temporally predictable patterns. This choice of temporal manipulation allowed them to investigate the effects of both the explicit and incidental encoding on memory. Their results supported that of Rohenkohl and colleagues (2012), but also critically showed that not only did temporally structured contexts have mnemonic benefits for incidental coding, but that performing the temporally structured task before the temporally unstructured task mitigate the negative effects on memory caused by proactive interference (Thavabalasingam et al., 2015).

In addition to these behavioral studies, several functional magnetic resonance imaging (fMRI) experiments are beginning to uncover the neural mechanisms responsible for these phenomena. One in particular conducted by Koppe and colleagues (2015) used emotional (angry and happy) and emotionally neutral faces in a set of two choice reaction task. In their study participants were told they would be making choices about the gender of the faces or the shape of geometric figures, but were blind to the temporal structure or

emotional stimuli manipulation. Like previous experiments, the researchers also created a temporally structured context using a constant ISI (4 s) and jittered ISIs for the unstructured condition and had participants complete both. Particularly, they found that while the ISI condition activated the amygdala and fronto-parietal region, both happy and angry emotional stimuli decreased activation in parietal areas, suggest a similar temporal mechanism. This study suggests that while temporal expectancy differentially impacts activity in the brain, processing of stimuli with different levels of arousal is the same (Koppe et al., 2015).

Many EEG studies are also looking at temporal expectancy and support the argument that it enhances early sensory components and possibly deepens memory encoding of visual stimuli (Jones and Ward, 2019; Rohenkohl and Nobre, 2011). Specifically, several recent studies corroborate evidence that temporal expectancy entrains neural activity by synchronizing it with regular temporal patterns, which seems to enhance the encoding of visual stimuli (Hickey et al., 2020) and influence the amplitudes of the key temporal, visual, and mnemonic markers such as the N2, P3, Late Positive Component (LPC), and Contingent Negative Variation (CNV) components (Hickey et al., 2020; Carvo et al., 2013).

Measuring Memorability

In addition to these studies, there is growing interest in memorability, defined as the probability, or likelihood, of a novel stimulus being remembered or forgotten (Bainbridge, 2019; Isola et al. 2014). A notable experiment by Isola and colleagues (2014) used a repeated detection task in the form of a memory game that allowed them to

measure and characterize memorability. This study was significant in many ways, namely it successfully assigned memorability scores to a diverse range of images, proved that the scores remained consistent across a large sample size and varying levels of time delays between initial encoding (i.e. decay factor), and created a memorability database for future researchers. The results from Isola and colleagues (2014) was followed by a similar study conducted by Khosla and colleagues (2015). Using similar principles, Khosla and colleagues (2015) automated the process for prediction of memorability through the creation of a Hybrid Convolutional Neural Network (CNN) called *MemNet*, and used it to develop the largest memorability database, *LaMem*, to date. It has been used by several studies and I propose it for the current study as well (Jo and Jeong, 2020; Mohsenzadeh et al., 2019).

Using these memorability databases, substantial knowledge has been gained about the properties that contribute to memorability. Surprisingly, low-level perceptual features and image statistics show little correlation with memory (Rust and Mehrpour, 2020). In fact, an fMRI study by Bainbridge and colleagues (2017) shows that there is little to no activation in areas associated with the early visual cortex and memorability. Rather numerous studies reveal that higher level properties and semantics are the most significant contributors to what makes an image memorable (Isola et al., 2014; Khosla et al., 2015; Rust and Mehrpour, 2020). Specifically, data suggest that distinctiveness, meaningfulness, popularity, salience, fixation map consistency, aesthetic, people/faces, interiors, human scaled objects, and images that evoke disgust or negative emotions all correlate with higher memorability (Isola et al., 2014; Khosla et al., 2015; Lyu et al.,

2020; Rust and Mehrpour, 2020). Crucially, there is substantial evidence that shows memorability is not only measurable, but predictable and consistent across humans and even rhesus monkeys (Bainbridge et al., 2013; Bainbridge, 2017; Isola et al., 2014; Khosla et al., 2015; Rust and Mehrpour, 2020).

While few, there are studies that have looked at the underlying neural activity connected to memorability. The Bainbridge and colleagues (2017) study mentioned above found that effects linked with memorability appear to be strongly associated with the medial temporal lobe (MTL). Additionally, a magnetoencephalography (MEG) experiment conducted by Mohsenzadeh and colleagues (2019) used a rapid serial visual presentation (RSVP) task in which participants completed two alternative forced choice detection task using faces as the target stimuli. Of note, this paradigm diminished the participants ability to fully view each image and participants were unaware of the subsequent memory test, thus encoding was incidental. Their findings reveal that despite the rapid viewing nature of the task, highly memorable stimuli were both more quickly perceived and processed, which they suggest indicates memorable images have more persistent representation in the brain across time.

These findings compliment those of an EEG study conducted by Cravo and colleagues (2017). In their study, although they do assess the memorability of their stimuli, they provide critical insight into the interaction between temporal associations and long-term memory through two cleverly designed experiments that combine elements the temporal expectancy, temporal bisection, and memory. The stimuli for this study combined complex scenes (of an interior room) with a dynamic go-target (a bomb that

that changed colors from blue to green at either 800 or 2000ms) or a no-go target (a bomb that changed from blue to red at 800 or 2000ms). The first experiment was a behavioral detection task, where participants learned the temporal association of the target events, which occurred in a fixed location and time unique to each scene. They were required to make their decision in 600 ms, encouraging quick but accurate responses. After learning these association, participants were given a memory task where they were shown the scene (without targets) and asked whether it was previously associated with a “short” or “long” interval target. Finally, participants took a temporal orienting task where they experienced the same scenes with targets, however only 67% of the targets were the same as in the learned section, the other 33% switched to the opposite interval that was previously associated with the target event (i.e. if the target event had a “short” interval in the learned section it became “long” interval in the temporal orienting task).

The second experiment was exactly the same, except they used EEG recordings and made it a discrimination task, so participants had to indicate whether the target changed colors to blue or green, using two separate key strokes. They found that participants were able to learn the complex temporal and scene associations as indicated by a decrease in RTs. Similarly, performance on the memory task across both studies showed that participants were able to encode reliable memories of temporal association for scene and targets. It is important to note that both learning and perceptual sensitivity was stronger for short intervals, possibly due to the dynamic context of the experiment which requires a higher resource load. Still this study has several significant implications for temporal expectations, memory, and time perception. Namely, its findings showed

that long-term memories not only inform what humans perceive but do so through temporal associations made in a predictable context. Additionally, it showed that temporal association stored in memory can effectively be used to optimize behavioral performance.

Current Research: Where do Time, Memory, and Expectation Collide?

Taken together, these findings provided strong evidence that memorable images have observable encoding and perceptual processing that are linked to better long-term storage and that temporal expectancy contributes to processing and mnemonic encoding benefits. Yet, despite the body of evidence highlighting the integral relationship between temporal expectancy, attention and memory, there have been no studies (to the best of my knowledge) that directly investigated how the inherent memorability of a stimulus specifically relates to time perception. Therefore, I believe a natural progression of research in this field is to further investigate the possible intersection of these psychological phenomena. The research at hand seeks to answer these distinct questions: How does temporal expectation, created through introducing stimuli in a temporally structured context, interact with the intrinsic memorability of an image? Furthermore, is memorability a property that itself could modulate perceived duration?

To address these questions, I conducted two simple behavioral studies. The first of which used a temporal bisection paradigm to examine whether the memorability of a visual stimuli modulates subjective duration judgments. The second study instead used a repeated-measure yes-no memory paradigm to investigate if the memorability of a visual stimulus is enhanced when viewed in a temporally structured framework. Based on the

previous research findings discussed above, I proposed that the intrinsic memorability of a visual stimulus will modify the encoding process and thus influence the subsequent operations involved in the subjective duration decision. Specifically, I predicted that in the context SET, highly memorable images will demand more attention and enhance encoding, which will lead to a higher accumulation of pulses and thus create an overestimation of perceived duration. Additionally, I predicted that temporal expectancy, created by a temporally structured framework, will enhance the memorability of images, such that stimuli with low memorability scores will be remembered better under a temporally structured context due to heightened attendance of the stimulus. Conversely, I hypothesized that stimuli with high memorability scores will again enhance encoding of the stimulus into reference memory, and thus reduce the negative effects of temporally unstructured frameworks seen in previous research.

METHOD FOR BOTH EXPERIMENT 1 AND EXPERIMENT 2

Participants

Experiment 1 included 28 neurologically healthy subjects (22 females, 4 males, average age=19.9) and Experiment 2 included 24 neurologically healthy subjects (19 females, 5 males, average age=20.5). One subject for Experiment 1 was later removed as an outlier, resulting in a final count of 27 subjects (21 females and 4 males). All subjects were recruited from the undergraduate student population of George Mason University (GMU). Participants were compensated with course credit through the cloud-based participant management software, Sona Systems. To participate in the study, subjects completed a questionnaire confirming they were between 18 and 60 years old, right-handed, and had normal or corrected-to-normal vision. Informed consent was obtained from all subjects before the experiment, and all data was collected in accordance with the standards of the Institutional Review Board at GMU.

Materials

Both experiments were coded using PsychoPy3 [v2020.2.10] and conducted via Pavlovia, the online behavioral sciences experiment platform. Although the exact specification of the testing platform used (i.e. Monitor type, keyboard/mouse configuration) was at the discretion of participants due to COVID-19 restrictions, I controlled for as many variables as possible by ensuring all subjects confirm that they had required equipment and also recommended ideal testing environments. The only

equipment necessary was a computer monitor for viewing the experiment and a keyboard to record participant responses, there were no additional software requirements.

EXPERIMENT 1: PERCEIVED DURATION AND MEMORABILITY

Stimuli

For this experiment, I used visual stimuli obtained from the Large-scale Memorability Dataset (LaMem) created by Khosla and colleagues (2015). Of note, *LaMem* consists of 60,000 images compiled from roughly 10 different databases (Khosla et al., 2015). By using images from diverse databases, Khosla and colleagues ensured their memorability scores accounted for a multitude of attributes (i.e. saliency, popularity, affect) and was consistent across a variety of scene types (i.e. scene-centric vs object-centric). Thus, the size and diversity of *LaMem* made it an attractive choice for the current research.

To select the stimuli, I split the database into seven different equally spaced bins ranging from high to low memorability [$\Delta_{\text{bin}} \sim 0.10390$; Bin 1 = 1 - .89610, Bin 2 = .89610 - .79220, Bin 3 = .79220 - .68831, Bin 4 = .68831 - .58441, Bin 5 = .58441 - .48051, Bin 6 = .48051 - .37662, Bin 7 = .37662 - .27273]. Due to the nature of the *LaMem* database it was not be feasible for each bin to have an equal number of images, however I randomly pick 28 images from each bin, ensuring a relatively equal distribution of memorability scores and scene type within the bins to the best of my ability. This resulted in 196 visual stimuli split into seven different categories of memorability, with Bin 1 having images with the highest memorability score and Bin 7 having the lowest. Each image appeared in RGB color space with a texture resolution of 512 at a .5 x .5 pixels.

Task

In Experiment 1, I investigated the interaction between the memorability of a visual stimuli and its perceived duration. To do this, participants performed a temporal bisection task, a simple design where subjects are asked to compare a temporal stimuli to a duration or set of durations that have been stored in their memory (Allen and Gibbon, 1991; Wearden and Ferrara, 1996). My experiment was similar in design to Wiener and colleagues (2014) however I only used visual stimuli. Due to the high number of trials, participants did not conduct practice trials to learn the reference durations. This paradigm has been used for decades to understand how humans perceive and process temporal information (Kopec and Brody, 2010) and served as an adequate method for addressing the question at hand. Namely, the task cleverly requires subjects to make four time and memory based mental calculations. First subjects must learn and encode reference durations into memory, next they must mentally measure the target stimuli duration, then retrieve the reference durations from their memory, and finally compare the target stimuli to their memory of the reference and make their judgment (Kopec and Brody, 2010).

At the start of each trial, participants were presented with a fixation point that appeared at the center of the screen for 500 ms before immediately presenting a visual stimulus. The stimuli order was randomized for each trial and images appeared for one of seven logarithmically spaced time intervals ranging from 300 to 900 milliseconds [300, 360, 432, 520, 624, 749, 900 ms]. Logarithmic spacing allows for more supra-geometric spread when visualizing the data (Kopec and Brody, 2010). Participants were tasked

with judging whether the stimulus presented was “short” or “long” based on their subjective threshold of the durations. They were directed to respond as quickly and accurately as possible using the “s” key for “short” and the “l” key for “long”. There was no response screen following the stimulus, participants were just instructed to answer as soon as the image disappeared. They did not receive feedback during this task and the next trial began upon their response. The combination of seven different memorability ranges and seven possible durations created a total of 49 possible conditions across 196 trials. Every image was seen at all seven durations, resulting in a total of 1372 trials, which was divided into seven blocks to allow participants a break. Thus, each trial was about six minutes making the full experiment ~45 minutes.

Data Analysis

To analyze the results, I used Matlab to create a psychometric curve for each of the participants based on the likelihood that they respond “long” (referred to as proportion long or $p(\text{long})$) for each of the durations intervals and within each memorability bin. Additionally, I collected the RT data to create a chronometric curve for each participant based on duration to evaluate the relationship between RT and memorability. Finally, using these data points I conducted a separate repeated measures ANOVAs with memorability and duration as factors.

Results

A repeated measures ANOVA on the $p(\text{long})$ using duration and memorability as the repeated measures factors (each 7 levels) revealed that as expected, the duration length that each images were presented at was significant across all memorability levels

($F_{(6,156)}=38.88, p < .001, \eta^2 = .38$), with images presented at longer durations perceived as longer and vis versa (see Figure 1). While memorability alone did not reach significance ($F_{(6,156)}=.78, p < .59, \eta^2 = 0$), there was a significant interaction between memorability and duration ($F_{(36,936)}=1.52, p < .027, \eta^2 = .004$). Although the effect size is small, these data suggest that the images with higher memorability scores, those that were in Bins 1-3, on average were perceived as lasting longer than the less memorable images in Bins 4-7 (see Table 1). Post Hoc analysis using Holm correction for p suggest that effect was only significant for the images at longer durations (i.e. 624, 749, and 900 ms).

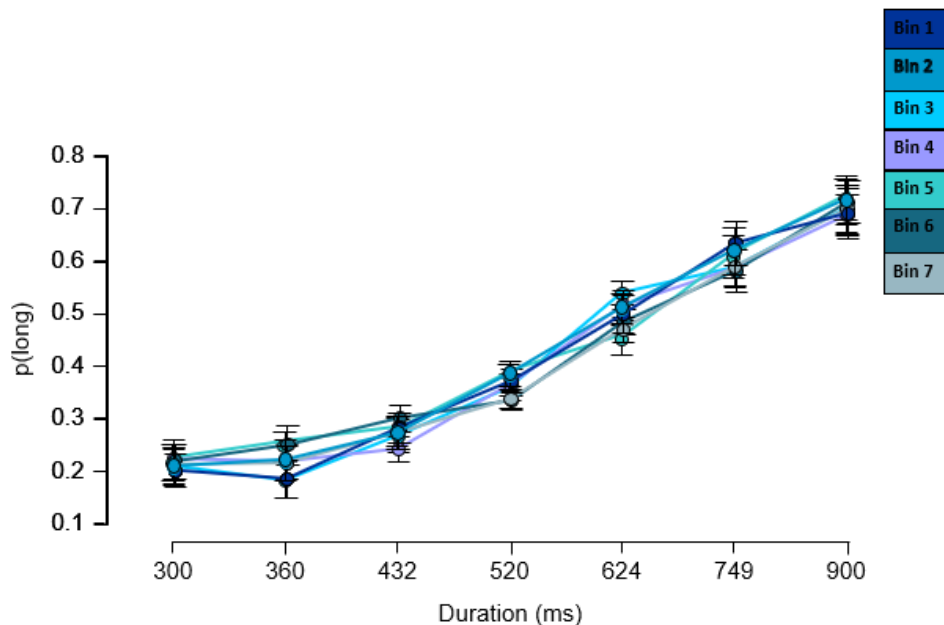


Figure 1 Psychometric Graph of $p(\text{long})$ by Duration for Each Memorability Bin with Standard Error Bars

Table 1 Simple Main Effects of Memorability on Duration

Simple Main Effects - Duration

Memorability	Sum of Squares	df	Mean Square	F	p
Bin 1	6.736	6	1.123	29.970	< .001
Bin 2	6.729	6	1.122	27.962	< .001
Bin 3	6.652	6	1.109	33.323	< .001
Bin 4	6.003	6	1.001	33.991	< .001
Bin 5	5.916	6	0.986	33.346	< .001
Bin 6	5.549	6	0.925	29.148	< .001
Bin 7	5.895	6	0.982	32.397	< .001

Note. Type III Sum of Squares

Additionally, analysis of the RT for each duration across all memorability bins revealed a significant main effect of duration ($F_{(6,156)}=3.38, p < .004, \eta^2 = .019$), but not memorability or for the interaction between the two ($F_{(6, 152)}=.204, p=.975, \eta=.000$ and $F_{(36,936)}=.834, p=.745, \eta=.004$ respectively). So, despite how memorable an image was, on average participants responded quicker to images presented at longer durations rather than shorter durations (see Figure 2).

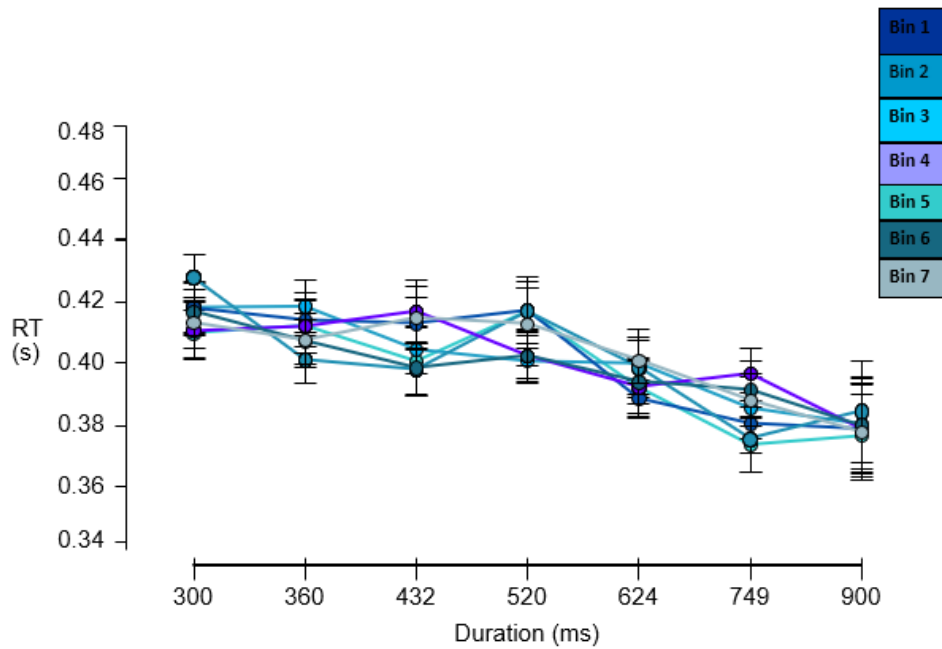


Figure 2 Mean RT for Each Duration by Memorability Bin with Standard Error Bars

While the results of this study do provide key insights to the answer of my initial question about how the unique quality of memorability might influence perceived time, it is necessary to observe the reverse relationship to gain a deeper understanding of the underlying temporal and mnemonic processes involved. To do this, my second study uses a recognition memory test to observe the role of perceived time on memorability.

EXPERIMENT 2: TEMPORAL EXPECTANCY AND MEMORABILITY

Stimuli

This experiment used the same set of 196 visual stimuli from Experiment 1 to reduce any possible confounds due to the possible nuances in memorability and scene category of different images.

Task

In Experiment 2, I examined how temporal expectation – created by viewing stimuli in a rhythmically structured context – influenced memorability. I investigated this question through a yes-no recognition memory task paradigm using a repeated-measures design modeled after Thavabalasingam and colleagues (2015). Image memorability has predominantly been explored through the recognition memory test paradigm, largely because it effectively captures a subject's memory performance using only two measures – the hit rate, H , and false alarm rate, FA (Bainbridge, 2020; Rust and Mehrpour, 2020). Similarly, several studies have used the same paradigm to provide evidence that rhythmic temporal structures enhance recognition memory (Hickey et al., 2020; Jones and Ward, 2019; Snodgrass and Corwin, 1988). Thus, a recognition memory test was a suitable paradigm to combine my interest of memorability and temporal pattern processing. Additionally, a repeated-measures design was ideal for this study because we must inherently create two conditions – a temporally structured (TS) context and a temporally unstructured (TU) context to accurately capture the relationship between

memorability and temporal expectation – so testing each subject in both conditions reduces the variability caused by individual differences.

Like the second experiment conducted by Thavabalasingam and colleagues (2015), each participant completed two blocks of a recognition memory task – one temporally structured and one temporally unstructured. Each participant also completed a single practice trial before the first block. After that, each block consisted of a study phase (where participants encoded the visual stimuli), a one-minute delay (where the participant completed simple math questions), and finally a test phase (where their memory performance was assessed). In the test phase participants were shown a stream of 48 images and told to remember them for a subsequent memory test. After the one-minute delay, there was a self-paced memory test where participants were shown all images from the test phase plus 48 additional novel distractor images. They were presented with each image individually and asked whether it was “New” or “Old”. Using their keyboard, they pushed “left arrow key” for “Old” images or “right arrow key” for “New”.

The order in which participants complete these blocks was counterbalanced, such that half completed the structured then the unstructured task (*TS-TU*) and the other half complete the task in the opposite order (*TU-TS*). Additionally, stimuli were not repeated across blocks, thus the *TS* and *TU* conditions for each participant contained 48 novel images in the test phase (each shown twice), followed by the same 48 images plus an additional 48 novel foil images in the study phase. In both conditions each image appeared for 700 ms. Like the original experiment, I counterbalanced both the images

used in each condition and the images used as targets and foils across all participants. This created 96 novel images and 192 trials per block and a total of 192 new images and 384 trials across both blocks (this does not include the single practice trial that uses 4 novel images, which will be discussed later).

While the task was explicitly labeled as a recognition memory test, participants were not be informed of the temporal manipulations or the differing levels of image memorability. To create the two temporal conditions without drawing attention to the difference Thavabalasingam and colleagues (2015) created a temporal pattern using rhythmic inter-stimulus intervals (ISIs) to construct the *TS* condition and arrhythmic jittered ISIs to construct the *TU* condition. The current study uses the same model by, the splitting the 196 image stimuli into mini sequences of four, with each sequence appearing twice in succession during the study phase. In both blocks, images appeared individually for a duration of 700 ms within their sequence. In the *TS* condition I created a temporal pattern for each sequence using the following ISIs: 100, 500, 1000, 2000 ms. Using a consistent ISIs and repeating each sequence twice should still implicitly increase the temporal predictability. Conversely, I jittered the ISIs in the *TU* condition using the mean of the four ISI durations listed above [SD for 100 = 40, SD for all other durations = 80 ms]. The jittered ISIs were randomized for each mini sequence as well as between the first and second presentation of the sequence. Jittering the ISIs using the mean duration of the constant ISIs allowed me to create similar ISI lengths between the two conditions while still making the presentation irregular to reduce temporal expectancy. Thus, if a

mini sequence consisted of images **A-B-C-D** then a trial in the *TS* vs *TU* conditions might look like:

TS: **A** – 100ms – **B** – 1000ms – **C** – 500ms – **D** – 2000ms – **A** – 100ms – **B** – 1000ms – **C** – 500ms – **D** – 2000ms

TU: **A** – 1525ms – **B** – 312ms – **C** – 118ms – **D** – 2418ms – **A** – 255ms – **B** – 2538ms – **C** – 426ms – **D** – 168ms

Before beginning the first block, participants completed a single trial practice round, matching the temporal context of that participants first block (e.g., if they were in the *TU-TS* group, their practice round was presented in the *TU* context). I added a practice round here to allow the use all 196 stimuli from the previous experiment while still adhering to the design used in Thavabalasingam and colleagues (2015). While I considered creating a rhythmic pattern using mini-sequences of seven to allow for an even split of the stimuli in each block, research shows that visual working memory is limited to roughly four objects at a time (Luck and Vogel, 1997). A future study might investigate the effect of longer temporal patterns in the structured framework. Another modification made to this study was the addition of a one-minute delay between the test and study phases of the task, similar to that of Jones and Ward (2019) and Jo and Jeong (2020). Adding this delay allowed me to test Thavabalasingam and colleagues' (2015) assumption that the mnemonic advantage of a temporal expectancy seen in their study would remain, or possible be enhanced, given an increased retention interval. Upon completion of the experiment, participants completed a questionnaire to probe for any indication of the temporal structure differences. Results of this survey suggested that virtually no subjects were aware of the manipulation. Each trial took approximately

seven minutes making the full experiment around ~15 minutes, not included time needed to complete the questionnaire and demographic information.

Data Analysis

Using principles from signal detection theory (SDT) with normal distribution, I measured recognition memory performance, or more specifically the discrimination index (d'). With the inclusion of the intersection bias measure, C , this model has proven to be acceptable and statistically significant across many similar paradigms (Snodgrass and Corwin, 1988; Hickey et al., 2020; Jones and Ward, 2019; Thavabalasingam et al., 2015; Carvo et al., 2017). Specifically, d' was calculated by subtracting the z score of the proportion of FA from the proportion of H [$d' = Z_H - Z_{FA}$]. Additionally, calculating C [$C = .5(Z_{FA} + Z_H)$] allows me to understand the nature of subject's decision, and possibly how that changes between the conditions and with respect to memorability (e.g., $C < 0$ indicates relaxed criteria for choosing "old" while $C > 0$ indicates more stringent criteria). I also calculated the accuracy for each participant for each level of memorability and within each condition. Using these data points, I ran three separate repeated measure ANOVAs on accuracy, d' , and C respectively each using condition, memorability, and condition order as main factors.

Results

The repeated measures ANOVA on accuracy using temporal condition (2 levels) and memorability (7 levels) as factors revealed a significant main effect of memorability ($F_{(6,132)}=7.00, p < .001, \eta^2 = .049$). Specifically, images with higher memorability indeed resulted in a higher number of hits. A Post Hoc analysis using Holm correction

for p revealed that the difference between recognition memory accuracy was largest between Bin 1 and Bins 4-7 (Bin 4: Mean Difference = .059, $p = .012$; Bin 5: Mean Difference = .089, $p = .001$; Bin 6: Mean Difference = .115, $p = .016$; Bin 7: Mean Difference = .129, $p = .002$) with participants having significantly higher hits for higher memorability bins in both conditions (see Figure 3 and Table 2). The results for condition did not reach significance ($F_{(1,22)} = 1.52$, $p < .230$, $\eta^2 = .005$) and there was also no significant interaction between the two factors ($F_{(6,132)} = .298$, $p < .937$, $\eta^2 = .001$). There was a significant simple effect of condition on memorability showing that while participants were more accurate when viewing images with high memorability in both conditions, accuracy was on average higher for all memorability levels when viewing the images in a temporally structured context as opposed to unstructured ($p < .001$). However, it is important to emphasize that the main interaction between condition and memorability was still insignificant, so further analysis is necessary to accurately interpret these results.

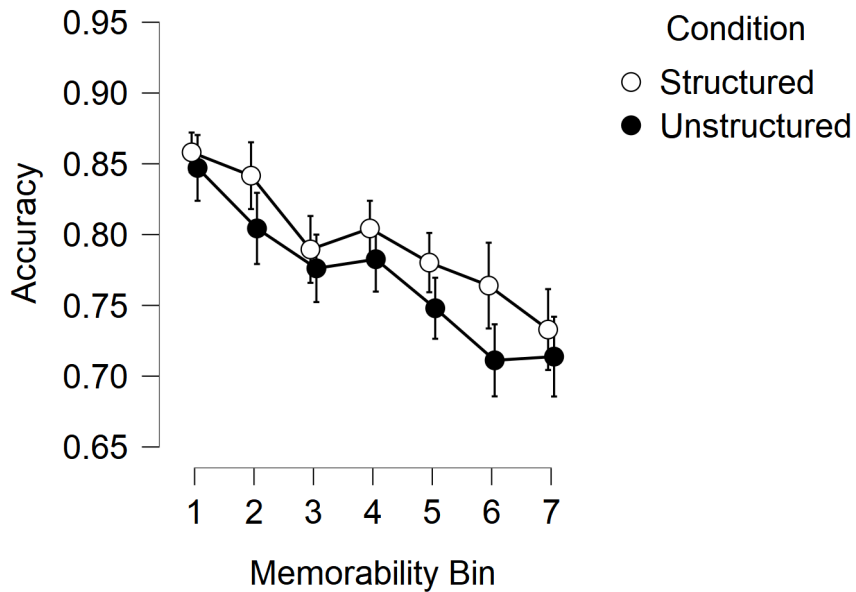


Figure 3 Repeated Measures ANOVA on Accuracy with Memorability as Main factor with Standard Error Bars

Table 2 Post Hoc Analysis with Holm Correction of p on Memorability Bin
Post Hoc Comparisons - Memorability Bin

		Mean Difference	SE	t	Cohen's d	P_{holm}
X1	X2	0.030	0.018	1.676	0.349	0.972
	X3	0.070	0.023	3.035	0.633	0.097
	X4	0.059	0.015	3.975	0.829	0.012*
	X5	0.089	0.018	4.997	1.042	0.001**
	X6	0.115	0.030	3.846	0.802	0.016*
	X7	0.129	0.028	4.663	0.972	0.002**

* $p < .05$, ** $p < .01$

Note. Cohen's d does not correct for multiple comparisons.

Note. P-value adjusted for comparing a family of 21

Note. Results are averaged over the levels of: Condition

The repeated measures ANOVA on d' yielded similar results, with a significant main effect of memorability ($F_{(6,132)}=6.73, p < .001, \eta^2 = .112$) and no significant effects of condition ($F_{(1,22)}=1.38, p < .252, \eta^2 = .010$) or the condition x memorability interaction ($F_{(6,132)}=.372, p < .846, \eta^2 = .005$). Again more memorable images resulted

in a higher d' , which I am used as a measure of subsequent recognition memory. Significantly, while condition did not reach significance as a factor, the recognition scores in the structured condition was higher across all memorability bin levels (see Figure 4A). Also of note is that participant performance declined in memorability Bins 5-7 in both conditions, however the decline in d' was noticeably worse in the unstructured condition. While the calculation for C did not reach significance, the general direction of the data appears to show that the criteria for selecting “old” did benefit from memorability (see Figure 4B).

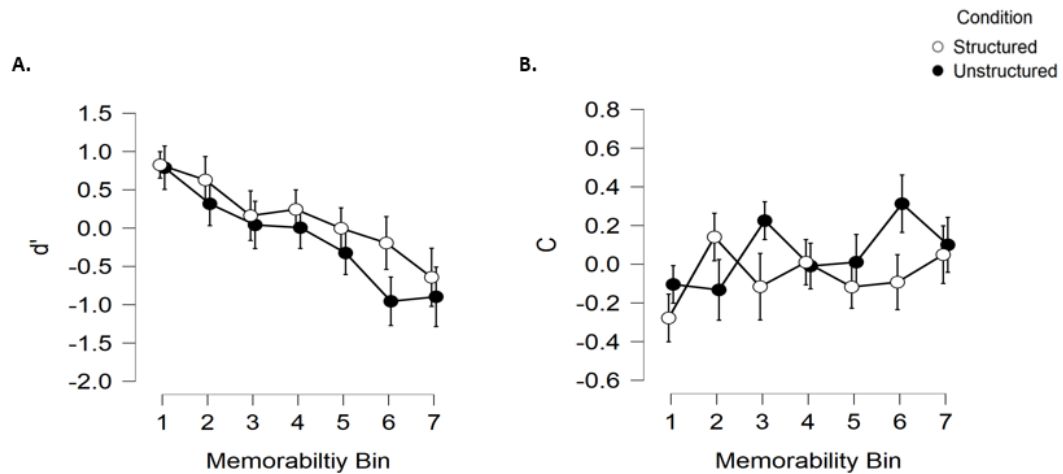


Figure 4 Main Effect of Memorability on d' (plot A) C (plot B) with Standard Error Bars

DISCUSSION

In conclusion I conducted two behavioral experiments investigating the interactions between subjective duration, memorability and temporal expectancy. For Experiment 1, I failed to reject the null hypothesis for RT, as there was no significant effect of memorability on how quickly participants responded. The results of Experiment 1 also did not support my original hypothesis that memorability would have a significant main effect on subjective duration, however the significant interaction effect found between memorability and duration length did modify subjective duration in the direction predicted. That is, while further analysis is necessary to reduce the noise currently being seen in this data set, participants did significantly report images with higher memorability as lasting for longer than lower memorability images at the same duration. Specifically, this effect was significant for the images at longer durations (i.e. 624, 749, and 900 ms). In other words, these data suggest that on average, highly memorable images are more likely to be perceived as lasting for longer durations than less memorable images.

This finding not only supports previous research by Dirnberger and colleagues (2012) that suggest a link between subjective duration and memory, but it also align with the idea that heightened arousal and attention, both of which are related to several qualities linked to high memorability (Isola et al., 2014; Khosla et al., 2015; Lyu et al., 2020; Rust and Mehrpour, 2020) are associated with overestimations of time (Gil and Droit-Volet, 2012; Droit-Volet et al., 2011; Ogden et al., 2015; Ogden et al., 2019; Zakay and Block, 1997). Additionally, it supports SET and aligns with the idea that image

memorability may be tied to encoding the duration of stimuli into reference memory and thus serves as a modifying factor for the accumulation of pulses which influence perceived duration. While the current research cannot reliably assess the extent of which arousal or attention might play a role in encoding for this effect, there are several possible theories. First, these findings suggest that the high-level visual properties and semantics associated with highly memorable images do not distract attention away from time and shorten perceived duration, as one might expect based on SET. Rather, they seem to lengthen perceived duration, suggesting a possible increase in either perceptual processing speed, deeper encoding or longer representation of the stimuli in reference memory, an acceleration accumulated pulses, or a combination of any of these. Future research looking at the role of specific properties of memorability involved in this effect are possible due to the comprehensive nature of *LaMem* and *MemNet* should be investigated.

The failure of memorability to independently reach significance and the presence of the interaction effect between memorability and duration also raises some new questions. Specifically, are more memorable images really being perceived as lasting longer or are these images instead more memorable because of an underlying timing process that makes them appear for longer? Furthermore, perhaps memorable images are not enhancing perceptual processing or persisting in reference memory for longer, but rather the attentional resources used in subjective duration decisions are being freed or optimized, and thus resulting in a bolstering or acceleration of the accumulator. A future study might further investigate the answers to these questions by adding additional

manipulations and conditions to memorability and duration. For example, given a paradigm where images with low memorability are controlled for with long durations and images with high memorability are controlled for with short durations, one could more closely assess the interaction between memorability and duration. Another potential area to expand upon for similar future studies is assessing the role that memory bias interference may play. In their temporal bisection task, Levy and colleagues (2015) found memory bias of reference durations correlated with variation of within subject bisection points, which allowed them to reinvestigate and revealing effects not previously seen in their uncorrected BP data.

While the main effect of temporal condition on accuracy and d' did not reach significance, the findings from Experiment 2 still supported my original hypothesis and replicated several of the finding by Thavabalasingam and colleagues (2015). Specifically, I found that there was a significant main effect of memorability on d' and a significant simple main effect of temporal condition on memorability. So as predicted, the structured temporal condition resulted in higher average d' scores (better recognition memory performance) across all memorability bins and on average d' was higher for more memorable images. This means that encoding the images in a temporally structured context did indeed improve recognition memory of images with lower memorability scores. Again, the criteria for decision threshold did not yield any significant results, but the data appears to show that the decision for recognizing an image as “Old” was lower for more memorable images. Additionally, these findings were significant even with a 1-minute delay between the encoding and testing phases of the recognition memory test,

which required images be held in reference memory for a longer amount of time than previous research. This suggest that not only are the underlying timing mechanisms in temporal expectancy capable of modifying or combatting factors that influence image memorability, but these mnemonic benefits can be sustained over a time.

The enhanced memory recognition performance observed in the structured condition supports previous research findings that encoding a stimulus in a rhythmic context enhances expectation and thus modifies the attentional resources allocated to it. Introducing memorability only provides further evidence in support of the mnemonic benefits of temporal expectation. Taken together, the implication of both studies suggest that highly memorable images possibly have at least some encoding benefits that enhance or modify attentional resources associated with temporal processes. Additionally, the qualities that make an image memorable do appear to be modulated by duration and temporal expectancy. While the extent of the role that attention and arousal play in timing specifically within the memorability of each of these images is unknown, there appears to be an underlying relationship between the two, with an increase in one resulting in an increase in the other.

One potential avenue of future research is Transcranial Magnetic Stimulation (TMS) of areas associated with these effects such as the medial temporal lobe and parietal lobe (Bainbridge et al., 2017; Wiener et al., 2012). Thus, an experiment focusing on stimulating these areas and documenting the subsequent results on the memorability and rhythmic priming effects may highlight the neural mechanisms that underpin these effects. Another interesting expansion of this study might include the use of eye-tracking

equipment based on findings in Lyu and colleagues (2020) which show that fixation map consistency and fixation count highly correlate with memorability. Specifically, in addition to the benefit of scene semantics, they found that higher fixation count during encoding and fixation maps that showed where participants were looking when viewing a scene both highly correlated with the participants memory of that scene (Lyu et al., 2020). Importantly, they only found these factors to be significant in the first 2 seconds of viewing. Investigating how viewing a stimulus at varying durations and with varying levels of memorability correlates with fixation might provide interesting insight into the neural linkages and direction of the relationship between memorability and subjective duration. Additionally, Jones and Ward (2019) identified the LPC component as predictive of memory performance when stimuli were viewed in a temporally structured context. Notably, this component has also been associated with perceived duration, seeing larger positive amplitudes correlating with shorter time estimates (Wiener and Thompson, 2015); a future EEG study might investigate any modulation to this component in a paradigm that manipulates the memorability of stimuli.

Finally, these findings may be further explored to help inform and enhance the level of scrutiny applied to determining the visual stimuli used for future researchers investigating the human perception of time. Together, insight from this study might serve as a steppingstone to valuable information about how external temporal associations of a visual stimuli might be confounded or enhanced by its inherent memorability. Information gleaned from this study may also serve to deepen the fields understanding of the relationship between attention and memory in SET. Finally, understanding how the

persistence of memorability and the perceptual processing advantages of temporal expectancy influence both mnemonic encoding and perceived duration could provide key details into how they work individually and provide insight into possible neural mechanisms they might share. Future research on the relationship between memorability and time will not only inform a critical aspect of how humans interact with the visual world, but also has wide range of practical applications including cognitive therapy treatments and possibly even business marketing.

REFERENCES

- Allan, L. G., & Gibbon, J. (1991). Human bisection at the geometric mean. *Learning and motivation*, 22(1–2), 39–58.
- Ayhan, I., Bruno, A., Nishida, S., & Johnston, A. (2011). Effect of the luminance signal on adaptation-based time compression. *Journal of Vision*, 11(7), 22.
- Bainbridge, W. A. (2020). The resiliency of image memorability: A predictor of memory separate from attention and priming. *Neuropsychologia*, 141, 107408.
- Bainbridge, W. A., Dilks, D. D., & Oliva, A. (2017). Memorability: A stimulus-driven perceptual neural signature distinctive from memory. *Neuroimage*, 149, 141–152.
- Bainbridge, W. A., Hall, E. H., & Baker, C. I. (2019). Drawings of real-world scenes during free recall reveal detailed object and spatial information in memory. *Nature Communications*, 10(1), 5.
- Bainbridge, W. A., Isola, P., & Oliva, A. (2013). The intrinsic memorability of face photographs. *Journal of Experimental Psychology: General*, 142(4), 1323–1334.
- Boltz, M. (1989). Time judgments of musical endings: effects of expectancies on the “filled interval effect”. *Perception & Psychophysics*, 46(5), 409–418.
- Boltz, M. G. (1993). Time estimation and expectancies. *Memory & Cognition*, 21(6), 853–863.
- 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.
- Cravo, A. M., Rohenkohl, G., Wyart, V., & Nobre, A. C. (2013). Temporal expectation enhances contrast sensitivity by phase entrainment of low-frequency oscillations in visual cortex. *The Journal of Neuroscience*, 33(9), 4002–4010.

- Dirnberger, G., Hesselmann, G., Roiser, J. P., Preminger, S., Jahanshahi, M., & Paz, R. (2012). Give it time: neural evidence for distorted time perception and enhanced memory encoding in emotional situations. *Neuroimage*, *63*(1), 591–599.
- Droit-Volet, S., Fayolle, S. L., & Gil, S. (2011). Emotion and time perception: effects of film-induced mood. *Frontiers in Integrative Neuroscience*, *5*, 33.
- Droit-Volet, S., & Meck, W. H. (2007). How emotions colour our perception of time. *Trends in Cognitive Sciences*, *11*(12), 504–513.
- Folta-Schoofs, K., Wolf, O. T., Treue, S., & Schoofs, D. (2014). Perceptual complexity, rather than valence or arousal accounts for distracter-induced overproductions of temporal durations. *Acta Psychologica*, *147*, 51–59.
- Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, *423*, 52–77.
- Gil, S., & Droit-Volet, S. (2012). Emotional time distortions: the fundamental role of arousal. *Cognition & emotion*, *26*(5), 847–862.
- Gladhill, K. A., Mioni, G., & Wiener, M. (2020). Dissociable Effects of Emotional Stimuli on Perception and Decision-Making for Time. *BioRxiv*.
- Hickey, P., Barnett-Young, A., Patel, A. D., & Race, E. (2020). Environmental rhythms orchestrate neural activity at multiple stages of processing during memory encoding: Evidence from event-related potentials. *BioRxiv*.
- Hickey, P., Merseal, H., Patel, A. D., & Race, E. (2020). Memory in time: Neural tracking of low-frequency rhythm dynamically modulates memory formation. *Neuroimage*, *213*, 116693.
- Isola, P., Jianxiong Xiao, Parikh, D., Torralba, A., & Oliva, A. (2014). What makes a photograph memorable? *IEEE transactions on pattern analysis and machine intelligence*, *36*(7), 1469–1482.
- Ivry, R. B., & Schlerf, J. E. (2008). Dedicated and intrinsic models of time perception. *Trends in Cognitive Sciences*, *12*(7), 273–280.

- Jo, S.-Y., & Jeong, J.-W. (2020). Prediction of Visual Memorability with EEG Signals: A Comparative Study. *Sensors (Basel, Switzerland)*, 20(9).
- Johnston, A., & Nishida, S. (2001). Time perception: brain time or event time? *Current Biology*, 11(11), R427-30.
- Jones, A., & Ward, E. V. (2019). Rhythmic temporal structure at encoding enhances recognition memory. *Journal of Cognitive Neuroscience*, 31(10), 1549–1562.
- Kafkas, A., & Montaldi, D. (2018). Expectation affects learning and modulates memory experience at retrieval. *Cognition*, 180, 123–134.
- Khosla, A., An, B., Lim, J. J., & Torralba, A. (2014). Looking beyond the visible scene. *2014 IEEE Conference on Computer Vision and Pattern Recognition* (pp. 3710–3717). Presented at the 2014 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), IEEE.
- Khosla, A., Raju, A. S., Torralba, A., & Oliva, A. (2015). Understanding and Predicting Image Memorability at a Large Scale. *2015 IEEE International Conference on Computer Vision (ICCV)* (pp. 2390–2398). Presented at the 2015 IEEE International Conference on Computer Vision (ICCV), IEEE.
- Kopec, C. D., & Brody, C. D. (2010). Human performance on the temporal bisection task. *Brain and Cognition*, 74(3), 262–272.
- Koppe, G., Heidel, A., Sammer, G., Bohus, M., Gallhofer, B., Kirsch, P., & Lis, S. (2015). Temporal unpredictability of a stimulus sequence and the processing of neutral and emotional stimuli. *Neuroimage*, 120, 214–224.
- Lake, J. I., LaBar, K. S., & Meck, W. H. (2016). Emotional modulation of interval timing and time perception. *Neuroscience and Biobehavioral Reviews*, 64, 403–420.
- Levy, J. M., Namboodiri, V. M. K., & Hussain Shuler, M. G. (2015). Memory bias in the temporal bisection point. *Frontiers in Integrative Neuroscience*, 9, 44.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390(6657), 279–281.

- Lui, M. A., Penney, T. B., & Schirmer, A. (2011). Emotion effects on timing: attention versus pacemaker accounts. *Plos One*, *6*(7), e21829.
- Lyu, M., Choe, K. W., Kardan, O., Kotabe, H. P., Henderson, J. M., & Berman, M. G. (2020). Overt attentional correlates of memorability of scene images and their relationships to scene semantics. *Journal of Vision*, *20*(9), 2.
- Mioni, G., Grondin, S., Bardi, L., & Stablum, F. (2020). Understanding time perception through non-invasive brain stimulation techniques: A review of studies. *Behavioural Brain Research*, *377*, 112232.
- Mohsenzadeh, Y., Mullin, C., Oliva, A., & Pantazis, D. (2019). The perceptual neural trace of memorable unseen scenes. *Scientific Reports*, *9*(1), 6033.
- Morrone, M. C., Ross, J., & Burr, D. (2005). Saccadic eye movements cause compression of time as well as space. *Nature Neuroscience*, *8*(7), 950–954.
- Ogden, R., Makin, A. D. J., Palumbo, L., & Bertamini, M. (2016). Symmetry lasts longer than random, but only for brief presentations. *i-Perception*, *7*(6), 2041669516676824.
- Ogden, Ruth S, Moore, D., Redfern, L., & McGlone, F. (2015). The effect of pain and the anticipation of pain on temporal perception: A role for attention and arousal. *Cognition & emotion*, *29*(5), 910–922.
- Ogden, Ruth Sarah, Henderson, J., McGlone, F., & Richter, M. (2019). Time distortion under threat: Sympathetic arousal predicts time distortion only in the context of negative, highly arousing stimuli. *Plos One*, *14*(5), e0216704.
- Palumbo, L., Ogden, R., Makin, A. D. J., & Bertamini, M. (2014). Examining visual complexity and its influence on perceived duration. *Journal of Vision*, *14*(14), 3.
- Palumbo, L., Ogden, R., Makin, A. D. J., & Bertamini, M. (2015). Does preference for abstract patterns relate to information processing and perceived duration? *i-Perception*, *6*(5), 2041669515604436.

- Rohenkohl, G., Cravo, A. M., Wyart, V., & Nobre, A. C. (2012). Temporal expectation improves the quality of sensory information. *The Journal of Neuroscience*, *32*(24), 8424–8428.
- Rohenkohl, G., & Nobre, A. C. (2011). α oscillations related to anticipatory attention follow temporal expectations. *The Journal of Neuroscience*, *31*(40), 14076–14084.
- Rust, N. C., & Mehrpour, V. (2020). Understanding Image Memorability. *Trends in Cognitive Sciences*, *24*(7), 557–568.
- Sasaki, K., & Yamada, Y. (2017). Regular Is Longer. *i-Perception*, *8*(5), 2041669517728944.
- Shimokawa, K., & Sugimori, E. (2019). Using virtual reality to study subjective time in crowded versus uncrowded environments. *Perceptual and Motor Skills*, *126*(5), 737–752.
- Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: applications to dementia and amnesia. *Journal of Experimental Psychology: General*, *117*(1), 34–50.
- Thavabalasingam, S., O’Neil, E. B., Zeng, Z., & Lee, A. C. H. (2015). Recognition Memory is Improved by a Structured Temporal Framework During Encoding. *Frontiers in Psychology*, *6*, 2062.
- Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, *66*(7), 1171–1189.
- Varakin, D. A., Klemes, K. J., & Porter, K. A. (2013). The effect of scene structure on time perception. *Quarterly Journal of Experimental Psychology*, *66*(8), 1639–1652.
- Wearden, J. H., & Ferrara, A. (1996). Stimulus range effects in temporal bisection by humans. *The Quarterly Journal of Experimental Psychology. B, Comparative and Physiological Psychology*, *49*(1), 24–44.

- Wiener, M., Klotz, D., Turkeltaub, P. E., Hamilton, R. H., Wolk, D. A., & Coslett, H. B. (2012). Parietal influence on temporal encoding indexed by simultaneous transcranial magnetic stimulation and electroencephalography. *The Journal of Neuroscience*, *32*(35), 12258–12267.
- Wiener, M., & Thompson, J. C. (2015). Repetition enhancement and memory effects for duration. *Neuroimage*, *113*, 268–278.
- Wiener, M., Thompson, J. C., & Coslett, H. B. (2014). Continuous carryover of temporal context dissociates response bias from perceptual influence for duration. *Plos One*, *9*(6), e100803.
- Xiao, J., Hays, J., Ehinger, K. A., Oliva, A., & Torralba, A. (2010). SUN database: Large-scale scene recognition from abbey to zoo. *2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition* (pp. 3485–3492). Presented at the 2010 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), IEEE.
- Zakay, D., & Block, R. A. (1997). Temporal Cognition. *Current Directions in Psychological Science*, *6*(1), 12–16.