Memorable beginnings, but forgettable endings:
Intrinsic scene memorability alters our subjective experience of time

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Abstract (167 words)

Time is the fabric of experience — yet it is incredibly malleable in the mind of the observer: seeming to drag on, or fly right by at different moments. One of the most influential drivers of temporal distortions is *attention*, where heightened attention dilates subjective time. But an equally important feature of subjective experience involves not just the objects of attention, but also what information gets tagged to be remembered or forgotten in the first place, independent of attention (i.e. intrinsic image memorability). Here we test how memorability influences time perception. Observers viewed scenes in an oddball paradigm, where the last scene could be a forgettable "oddball" amidst memorable ones, or vice versa. Subjective time dilation occurred only for *forgettable* oddballs, but not memorable ones — demonstrating an oddball effect where the oddball did not differ in low-level visual features, image category, or even subjective memorability. But more importantly, these results emphasize how memory can interact with temporal experience: forgettable endings amidst memorable sequences dilate our experience of time.

Keywords

time perception; time dilation; oddball effect; memorability; scene perception

1. Introduction

Subjective time is malleable. Our experience of time can be distorted by a wide array of factors (such as stimulus intensity, complexity, or magnitude; for a review, see Matthew & Meck, 2016). Of all these factors, however, the most common cognitive explanation for why time flies or drags on involves *attention* (Zakay & Block, 1996). When attention is heightened for a particular event, previous studies have suggested that we process more information per unit of objective time (e.g. Wutz et al., 2015), which in turn dilates our experience of time. The influence of attention can be powerful — attending to the passage of time itself increases people's duration estimates (e.g. Fraisse, 1984). The effects of attention on time perception have also been documented repeatedly in laboratory settings — perhaps most famously through the "oddball effect", where a perceptually distinct "oddball" (such as a square amidst circles) captures attention, and is in turn experienced to last longer than its non-oddball counterparts (Tse et al., 2004).

An equally important process in subjective experience, however, is not just how we are *attending* to what is currently happening, but also how we are *remembering* one moment to the next. As a result, a great deal of work has also investigated the relationship between memory and time perception. Remembering durations of time can produce completely different duration estimates compared to attending to a duration as it is unfolding (for a review see Block & Zakay, 1997; Block & Gruber, 2014; Wearden, 2016). Beyond recalling durations, memory can also influence time perception by way of prior exposure. Stimuli that are repeatedly shown to people are experienced to last for shorter durations than they actually did (e.g. Matthews, 2011). Conversely, stimuli that match information being actively maintained in working memory (e.g. Bi et al., 2014), or that have been encoded into long-term memory (e.g. Witherspoon & Allan, 1985) are experienced to last longer than stimuli that have not been encoded into memory.

These studies on memory and time have focused on durations or specific events *in the past*. But faced with an influx of information at any given moment *in the present*, we must determine what information to remember and what to forget in the first place. This likelihood of information being tagged to be remembered or forgotten is reflected in a stimulus property called *memorability*. Memorability is a measurable, stable quality of a wide range of naturalistic stimuli — from faces (e.g. Bainbridge et al., 2013), scenes (e.g. Isola et al., 2011), to dynamic videos of dance (Ongchoco et al., 2022) — and it reflects how likely a stimulus is to be remembered or forgotten across people. People have limited insight into which images are “memorable” or “forgettable” (e.g. Bainbridge et al., 2013; Isola et al., 2013; although see Undorf & Bröder, 2021; Saito et al., 2022), and memorability is independent of mere novelty, arousal, or attention (for a review see Bainbridge, 2019; Bainbridge, 2020; Isola et al., 2011). In fact, memorability has been shown to be a stronger determinant of memory than people’s attentional states (Wakeland-Hart et al., 2022), and it may reflect how easy it is to process an image (Goetschalckx et al., 2019; Xie et al., 2020). Just as attention selects what information is processed for conscious awareness, memorability selects what information goes on to be stored.

To the extent that our subjective experience of time is determined by how much information is processed per unit of objective time, an important question must be just what “processing” entails here. It seems possible that what information is processed may differ between attention and memory. After all, we can attend to information that does will not be further remembered, and we can remember information that may not always be the most attention-grabbing. If this is the case, then memorability might play an independent role from attention in terms of how much information is processed, which in turn could determine our subjective experience of time. This possibility has never been explored because information processing accounts of time perception have tended to focus on attention or memory for specific prior events. Here we ask how our perception of time might be influenced by the *memorability* of stimuli during perception (rather than attention). In Experiments 1a-b, we asked whether memorability might distort *relative* time judgments in an oddball paradigm (Tse et al., 2004). In Experiment 2, we probe whether observers can report what is memorable or not in the experiment — and whether and how correctly reporting the memorable image might predict its impact on time perception.

2. Experiment 1a: Memorability on Relative Time Judgments

Observers saw four images appear sequentially, and were asked whether the last image lasted longer or shorter than the others (see Tse et al., 2004). Unbeknownst to them, the durations of the four images were always the same, and on critical "oddball" trials, the last image varied in memorability from the rest of the other images (such that it could be highly forgettable in a stream of memorable images, or vice versa). If memorability exerts an influence on time perception, then the perceived duration of the last image in oddball trials should systematically differ from that of the other images. We chose a relative time judgment task here because pilot work showed that absolute time judgments may not be sensitive enough (or may be too noisy) to capture a subtle effect (see Supplementary Information).

2.1 Method

2.1.1. Participants. 126 observers were recruited using the Prolific online platform. All observers were fluent English speakers above 18 years of age from the United States. This sample size was determined from a power analysis conducted based on time perception experiments run by Saurels et al. (2020) that determined an effect size of Cohen's d=0.55, combined with a power level of 95%. This analysis suggested a sample size of 63, which we doubled to reduce risks of low data quality from online testing. All experimental methods and procedures were approved by the University of Chicago Institutional Review Board.

2.1.2. Apparatus. Observers were directed to a website where stimulus presentation and data collection were controlled via custom software written using a combination of HTML, CSS, JavaScript, PHP, and JsPsych libraries (de Leeuw, 2015). Observers completed the experiment in fullscreen mode on either a laptop or desktop computer.

2.1.3. Stimuli. Images and their memorability scores (hit rates, HR, in a continuous recognition task) were obtained from a dataset by Isola et al. (2011). For 40 different scene categories, pairs of memorable and forgettable images were selected, with the 40 memorable images with HRs from 0.812 to 0.906, and the 40 forgettable images with HRs from 0.360 to 0.536. Thus, for a given scene category (e.g., "lake"), there were corresponding memorable and forgettable images (**Figure 1**). Scene categories varied widely, incorporating natural and manmade scenes, as well as indoor and outdoor scenes. Memorable and forgettable images were matched for low-level visual properties of spatial frequency and color, using the Natural Image Statistical Toolbox (Bainbridge & Oliva, 2015), and presented at a size of 500 x 500 pixels.

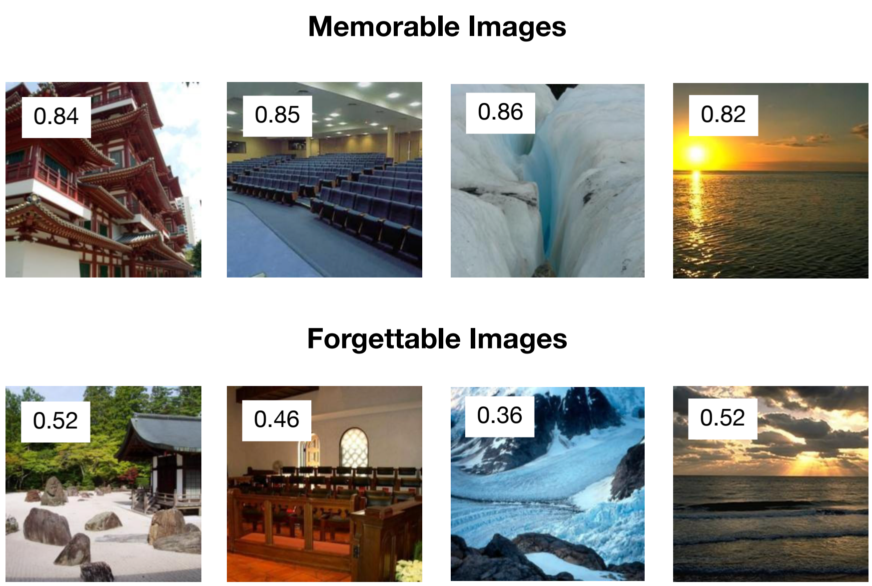

Figure 1 Examples of memorable (top) and forgettable (bottom) image pairs. Memorability scores for "forgettable" images ranged from 0.360 to 0.536. Memorability scores for "memorable" images ranged from 0.812 to 0.906. Image pairs always contained a memorable version and a forgettable version of the same scene category — e.g., an image pair may contain a memorable sunset (top row, right*)* and a forgettable sunset (bottom row, right*)*. Image set and memorability scores were obtained from Isola *et al.,* 2011.

2.1.4. Procedure and Design. Each trial began with a 950ms fixation cross. Observers were presented with four images that appeared one after another, presented with the same duration (850, 950, 1050, or 1150ms, randomly selected for each trial), with a 950ms fixation cross between each image. Durations were chosen based on previous work (New & Scholl, 2009; Tse et al., 2004). The first three images were drawn from either the Memorable image set (i.e. MMM), or the Forgettable image set (i.e. FFF). In the Oddball-Absent condition, the last image was drawn from the same set as the previous three images (i.e. MMMM and FFFF). In the Oddball-Present condition, the last image was drawn from the opposite image set (i.e. MMMF and FFFM, where the last image was then an "oddball" in memorability). After a 500ms blank delay, observers pressed a key to indicate whether the final image was longer or shorter in duration than the images that came before it (**Figure 2**). Images were counterbalanced by scene category across participants, so that each participant only saw one image from each of the 40 scene categories. This ensures that any differences are due to the memorability of the images themselves, and not low-level visual differences, or differences based on scene category.

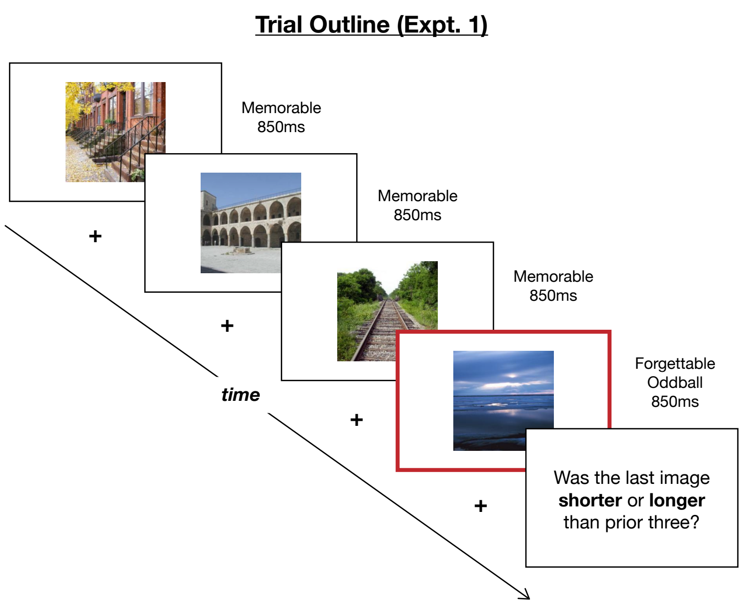

Figure 2 Trial flow. Four images were presented one at a time. After viewing the fourth image, observers were asked whether the fourth image was longer or shorter in duration than the prior three images.

Observers completed a single practice trial, and then 20 experimental trials (presented in a random order for each observer): 4 durations (850, 950, 1050, or 1150ms) x 4 possible image sequences (MMMM, MMMF, FFFF, or FFFM), together with 4 "catch" trials interspersed across the 16 trials. Catch trials were designed to have a clear time duration difference between the last image and the preceding three images (850ms versus 1150ms), to give observers confidence with the task and to serve as a performance check.

2.2 Results

Observers who performed at chance or below for the catch trials, as well as those who pressed the "s" key or "l" key for more 85% of the time, were excluded from analysis (n=10). For each trial, we coded responses with 1 if the duration of the last image was reported as being longer than the others, and 0 if it was reported as being shorter than the others. The probability of reporting that the last image was longer is reflected in **Figure 3a**, with proportions at chance (50%) for durations below 1000 (which is what we would expect given that images were of the same duration) — and these proportions increasing for durations above 1000. This is consistent with previous oddball work showing that longer durations tend to be perceived as longer (New & Scholl, 2009). The critical measure then lies in the *differences* between the oddball and non-oddball trials. We computed the difference between people's responses in the Oddball-Present trial versus in the Oddball-Absent trial for each duration (850, 950, 1050, 1150ms) and each memorability condition (when the sequence ended with a memorable image, or a forgettable one). This resulted in 8 difference values (4 duration conditions x 2 memorability conditions), depicted in **Figure 3b**. Positive values indicate *oddball-induced dilation*, such that people reported the image in the Oddball-Present trial as having lasted longer, but not in its counterpart Oddball-Absent trial.

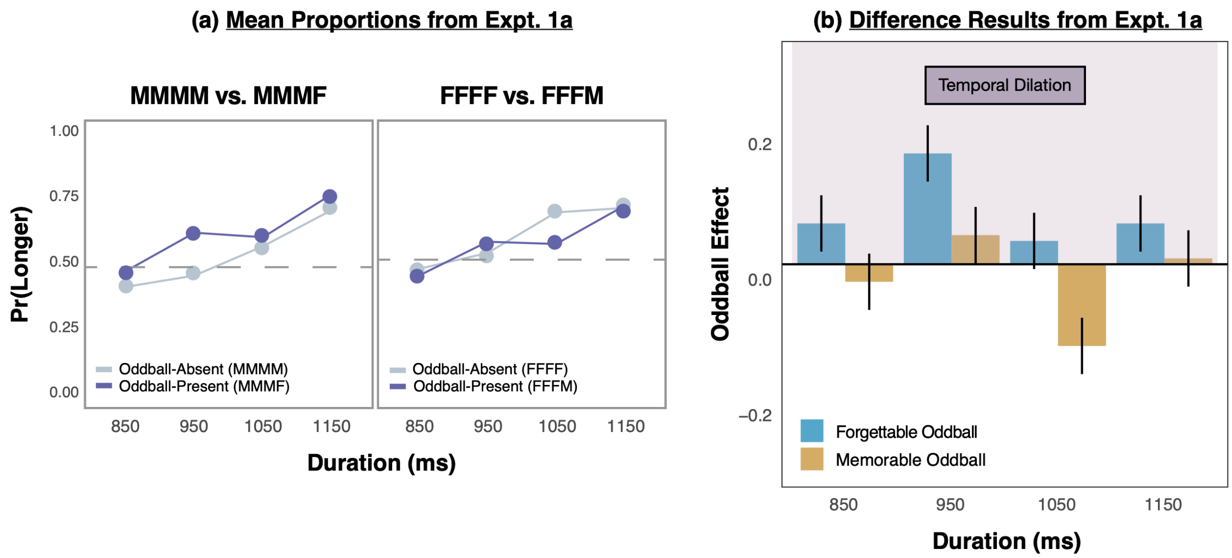

Figure 3 Results for Experiment 1a. (a) The plot depicts the proportion the last image in the sequence was reported as lasting longer — with chance at 50%. (b) The plot depicts the average oddball effects across various stimulus durations, broken down by whether the sequence involves a forgettable (blue) or memorable (yellow) oddball. The purple shaded region reflects conditions that show temporal dilation. Error bars reflect standard errors of the mean.

Sequences with forgettable oddballs (blue bars) showed positive subjective time dilation relative to their oddball-absent counterparts for all four duration conditions. In contrast, sequences with memorable oddballs (yellow bars) showed inconsistent results across durations. A three-way ANOVA confirmed that there was a reliable main effect of duration (F(1, 115)=83.75, p<.001, η_p^2=.089), no main effect of memorability (i.e. whether the last image was memorable; F(1, 115)=0.85, p=.359), and no main effect of the oddball (i.e. whether the last image was an oddball; F(1, 115)=1.50, p=.223) — but there was a significant interaction between memorability and the presence of an oddball (F(1, 115)=7.31, p=.008, η_p^2=.007), with no other significant interactions for any of the other variables. Specifically, there was a reliable oddball effect for forgettable oddballs (relative to 0: t(115)=2.58, p=.011, d=.24) — but not for memorable oddballs (relative to 0: t(115)=0.83, p=.412, d=.08).

2.3 Discussion

This experiment reveals two key results. First, subjective time perception was sensitive to oddballs determined by the memorability of the images. This is the first study, to our knowledge, to show an oddball effect where the oddball does not differ in low-level visual features, image category, or even perceived differences in memorability (Isola et al., 2013). In other words, the oddballs were not effectively "odd" — but we observe the oddball effect anyway. Second, there was an asymmetry between memorable and forgettable oddballs, such that only forgettable (but not memorable) oddballs showed the oddball effect. As we discuss later, this reveals new insights about the oddball effect: that it is a function not just of attention — but also of memory.

3. Experiment 1b: Direct Replication

This experiment was a direct replication of Experiment 1a. 126 new observers participated (with this sample size chosen to exactly match that of Experiment 1a). Observers who performed at chance or below for the catch trials, as well as those who pressed the "s" key or "l" key for more 85% of the time, were excluded from analysis (n=7). The probability of reporting that the last image was longer is reflected in **Figure 4a**, and the 8 difference values (4 duration conditions x 2 memorability conditions) are depicted in **Figure 4b**. A three-way ANOVA confirmed that there was a reliable main effect of duration ($F(1, 118)=55.88$, $p<.001$, $\eta_p^2=.086$), no main effect of memorability (i.e. whether the last image was memorable; $F(1, 118)=0.46$, $p=.501$), and no main effect of the oddball (i.e. whether the last image was an oddball; $F(1, 118)=0.84$, $p=.361$) — but there was again a significant interaction between memorability and the presence of an oddball ($F(1, 118)=4.36$, $p=.039$, $\eta_p^2=.004$), with no other significant interactions for any of the other variables. Specifically, there was a reliable oddball effect for forgettable oddballs (relative to 0: $t(118)=2.12$, $p=.036$, $d=.19$) — but not for memorable oddballs (relative to 0: $t(118)=0.77$, $p=.440$, $d=.07$). This direct replication showed the same pattern of results as those in Experiment 1a.

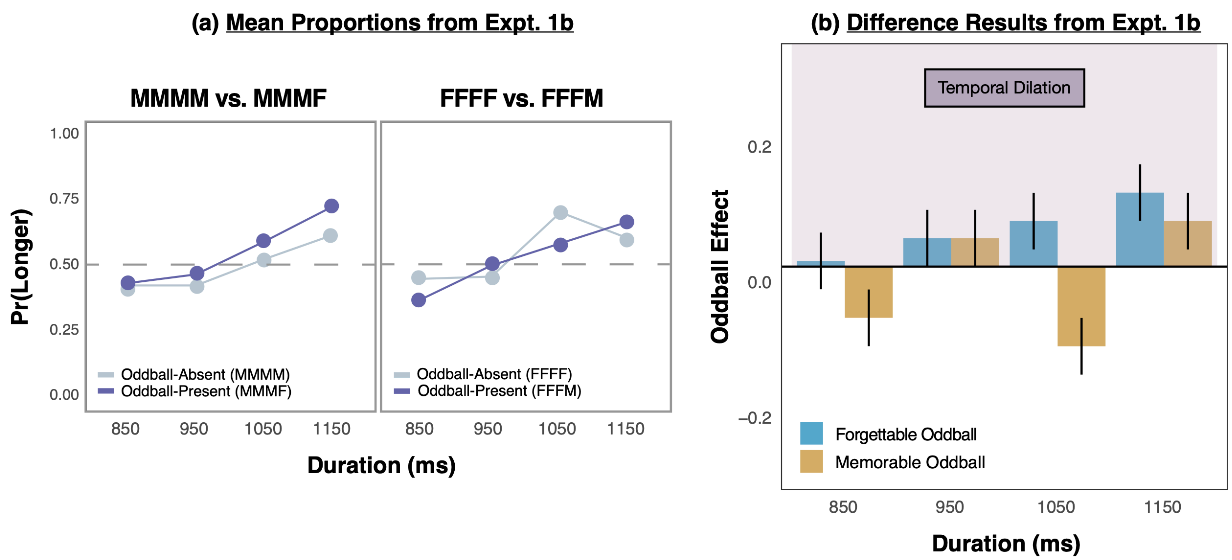

Figure 4 Results for Experiment 1b.

4. Experiment 2: Relative Time Judgments against Odd-One-Out Responses

In Experiment 1 and its direct replication, we observed oddball effects for *forgettable* oddballs, but not for memorable ones. These results are striking especially since previous work has suggested that people do not have insight into which images are memorable or not in the first place — and so they demonstrate oddball effects without the characteristic of something being 'odd'. But do people actually really have no insight to which image is 'odd'? Here we added a final task in which observers were asked to report which image does not belong of four images (corresponding to the images that the observers saw in the time judgment task).

4.1 Method

This experiment was a direct replication of Experiments 1a-b. 126 new observers participated (with this sample size chosen to exactly match that of Experiments 1a-b). After the time judgment task, observers then completed an "odd-one-out" task, where they were presented four images at a time (corresponding to the four images they saw on each trial in the time judgment task) in a 2x2 grid (with the position of the images randomly determined in each trial). Observers simply had to select which of the four images "does not belong", with no other instructions beyond this.

4.2 Results

Observers who performed at chance or below for the catch trials, as well as those who pressed the "s" key or "l" key for more 85% of the time, were excluded from analysis (n=16). The probability of reporting that the last image was longer is reflected in **Figure 5a**, and the 8 difference values (4 duration conditions x 2 memorability conditions) are depicted in **Figure 5b**. A three-way ANOVA confirmed that there was a reliable main effect of duration ($F(1, 109)=25.78$, $p<.001$, $\eta_p^2=.048$), no main effect of memorability (i.e. whether the last image was memorable; $F(1, 109)=0.05$, $p=.829$), and no main effect of the oddball (i.e. whether the last image was an oddball; $F(1, 109)=0.06$, $p=.800$) — but there was a significant interaction between memorability and the presence of an oddball ($F(1, 109)=6.94$, $p=.010$, $\eta_p^2=.006$), with no other significant interactions for any of the other variables. Specifically, there was a reliable oddball effect for forgettable oddballs (relative to 0: $t(109)=2.01$, $p=.047$, $d=.19$) — but not for memorable oddballs (relative to 0: $t(109)=1.39$, $p=.166$, $d=.13$). In the odd-one-out task, mean accuracy (for selecting the right 'oddball' image) for forgettable oddballs was 21.36% (SD=20.83%; compared to chance 25%, $t(109)=1.83$, $p=.070$) and for memorable oddballs was 29.32% (SD=22.17%; compared to chance 25%, $t(109)=2.04$, $p=.043$). Thus, for the key condition that shows time dilation (the forgettable oddball condition), forgettable oddballs were not recognized as oddballs. Mean accuracy per subject did not predict the magnitude of dilation for forgettable oddballs ($r=.005$, $p=.961$) or memorable oddballs ($r=.002$, $p=.981$).

4.3 Discussion

These results serve as another replication of the effects from Experiments 1a and 1b. Moreover, they confirm the limited insight that observers have into which images are the memorable or forgettable oddballs in the set.

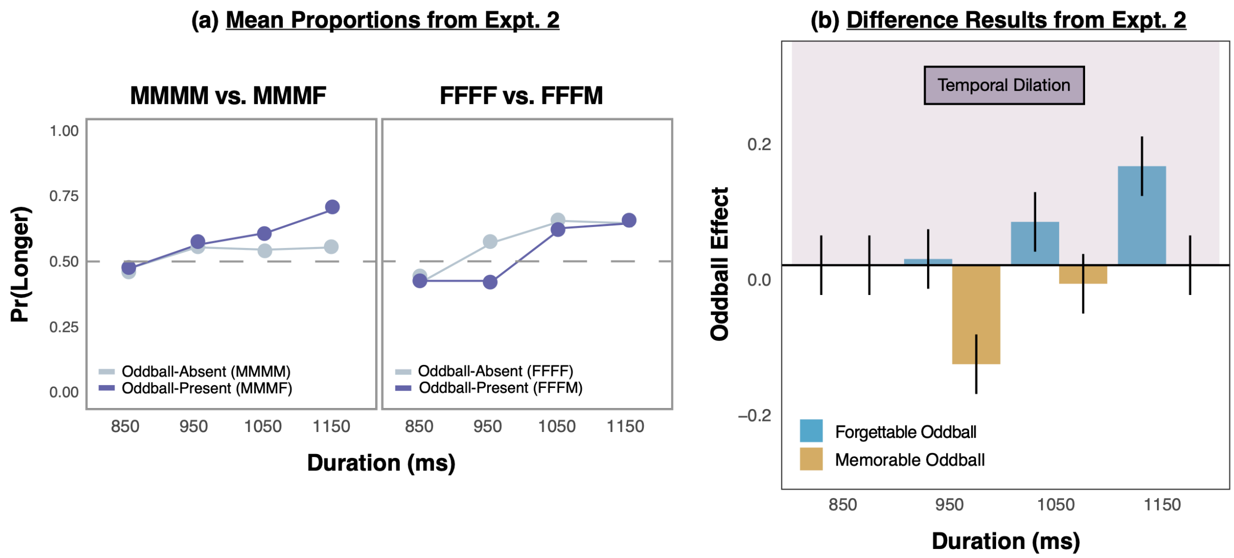

Figure 5 Results for Experiment 2.

5. General Discussion

The experiments here suggest three key results. First, memorability can influence time perception — and produce oddball effects, even in the absence of salient and obvious oddballs. Second, there was an asymmetry between forgettable versus memorable oddballs. And third, observers had limited insight into which images were forgettable versus memorable oddballs.

These results collectively suggest an independent role of memory (especially memorability) on subjective time perception, above and beyond attention and predictability. In particular, the oddball effect is often explained by one of two explanations (for a review, see Ulrich & Bausenhart, 2019): the oddball may seem to last longer than its non-oddball counterparts because the preceding repetitive stimuli are experienced as lasting shorter than they did (Pariyadath & Eagleman, 2008); and/or the oddball, being sudden, salient, and unexpected, receives more attention than the other predictable stimuli (Tse et al., 2004). Neither of these explanations readily apply to the oddball effects in the present study, since the current effects occurred in sequences of heterogenous stimuli (with no overt repetition in the images), where the oddball was also not defined by a salient (attention-grabbing) change. In fact, when asked what the experiment was about, observers mentioned the potential influences of "natural or manmade environments", "whether an object is close or far away", "similar pictures" on time perception — but no one mentioned the "memorability of images" — and when asked to report which image was the 'oddball', observers barely performed above chance.

The asymmetry between forgettable and memorable oddballs further emphasizes the role of memory. If the effect were just due to attention to a change in image features, then we should have seen oddball effects for both forgettable and memorable oddballs. We speculate that the observed asymmetry in effects may be a function of *encoding* in memory. Prior work has suggested that memorable images are more efficiently encoded than forgettable ones (Bainbridge et al., 2017; Goetschalckx et al., 2019; Xie et al., 2020). The forgettable oddballs may have then seemed to last longer because they required more resources to encode relative to preceding memorable images — which would be consistent with other work showing that cognitive processing increases perceived duration (Wehrman & Sowman, 2019). In contrast, in sequences with memorable oddballs, the processing required for the preceding forgettable images may have increased overall cognitive load, or even disengaged encoding altogether — leading to no reliable differences in subjective time perception. This "disengaging" is reminiscent of previous work where learning may be disengaged when we have learned that there is nothing to learn — such that the absence of regularities early on in a learning phase may preclude the learning of regularities later on (Junge et al., 2007). By extension, it might not make sense to keep looking out for things to remember if we have learned that there is nothing to remember. Thus, some moments may capture our attention more than others — but perhaps just as critical is how these moments are tagged to be remembered or forgotten in the end.

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Author Contributions

MG, JDKO, and WAB designed the research and wrote the manuscript. MG and JDKO conducted the experiments and analyzed the data with input from WAB.

Open Practices

All data will be available in the Supplementary Raw Data Archive included with this submission.

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Disclosure Statement

The authors report there are no competing interests to declare.