

On the Clock?

An Empirical Investigation of Psychological Time Distortions

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To read is to voyage through time."

— **Carl Sagan,** Cosmos, Episode 11: The Persistence of Memory

DEDICATIONS

To my late grandmother, for spending countless hours listening to my ideas,
but never having the chance to see where they led.

And to Dad, for encouraging my earliest wonder about the universe;
a wonder that eventually turned inward, toward the mind.

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Preface

As primary investigator, I was responsible for the experimental designs, data collection, data analyses, and writing of this thesis. My supervisor, Dr. Denis Cousineau, provided guidance, recommendations, and feedback regarding all aspects of the thesis. My master's thesis supervisor, Dr. Guy Lacroix, provided guidance for the design of the first experiment. Mohammed Aswad, Rachel Moreau, and Vijay Robinson assisted with data collection for Experiment 1 at Carleton University. Francesco Dunn, Christina Barber, Saima Mujeebuddin, and Meaghan O'Hara assisted with data collection for Experiment 1 at the University of Ottawa. All experiments received approval from the research ethics boards at Carleton University (Experiment 1) and at the University of Ottawa (Experiments 1, 2, & 3).

Abstract

The study of time perception typically involves asking people to guess how long a task took to complete. This is called a *duration estimate*. The accuracy of their estimate is then compared with the actual task's duration. This approach is widely used for brief tasks and it underpins several models of psychological time distortion. However, duration estimates may not fully capture the subjective experience of time. This thesis was thus an investigation into additional measures of temporal experience (*estimate uncertainty* and *passage of time judgements*). These measures were tested across varying experimental conditions (increasingly longer task durations; levels of task difficulty; intentional vs. incidental encoding of time). The first chapter of this thesis synthesizes the extant literature on duration estimates, estimate uncertainty, and passage of time judgements. The second chapter outlines a series of three experiments investigating two main questions: 1) At what timescales traditional models accurately predict duration estimation? 2) Under what conditions are passage of time judgments and duration estimates related? The third chapter synthesizes and discusses the results. Although there was no direct, consistent relationship between subjective *pace of time* experienced throughout the task (passage of time judgements) and duration estimate accuracy across experiments, an indirect relationship emerged. The two forms of time judgements are perhaps indirectly related through the information processing demands of the task. Passage of time judgements rely heavily on internal task appraisals (e.g., boredom), which vary with task difficulty and duration, whereas duration estimates fit better within traditional models of time perception that predict estimation accuracy in single-task versus dual-task conditions. Together, these findings highlight important distinctions between different forms of temporal judgment and provides insight into the complexity of how time is experienced and reported.

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CHAPTER 1: LITERATURE REVIEW

Our perception of time is frequently distorted. Distortions are evidenced not only in colloquial phrases like "time flew" or "time stood still," but also by experimental evidence (some even empirically testing whether a "watched pot" boils; Block, George, & Reed, 1980). Decades of research have focused on conditions that result in time distortions (e.g., Fraisse, 1984; Ornstein, 1969). Typically, time distortions are measured after individuals engage in a task (e.g., a Stroop task; Zakay & Fallach, 1984). At the end of the task, participants translate their experience into a judgement of time, called a *duration estimate* (Zakay & Block, 1997). Researchers can thus compare duration estimates (often provided verbally by the participant) with objective clock time to determine whether a psychological distortion of time has occurred.

A myriad of experimental factors influence the accuracy of a duration estimate, including whether participants are explicitly instructed to attend to time during the experiment (Hicks, Miller, & Kinsborne, 1976). Duration estimates are also affected by task length (e.g., Tobin et al., 2010) and cognitive load (e.g., task difficulty; Block et al., 2010). However, the accuracy of a duration estimate does not necessarily capture a person's subjective time distortions. For instance, in a short task (e.g., waiting in line), one might know that only a short time has elapsed and thus provide a short (accurate) duration estimate. Yet the person might *feel* as though time has passed slowly. In fact, time tends to feel slower if the task is perceived as boring (Tanaka & Yotsumoto, 2017; Walker, 2019).

The perceived pace at which time passes changes across contexts, such as during heightened negative emotional states like fear (Fayolle, Gil, & Droit-Volet, 2015) or with greater knowledge of our own timing bias (Lamotte, Izaute, & Droit-Volet, 2012). Therefore, people might strategize when providing a duration estimate based on the emotional valence of the task,

or to correct for potential bias in their responses (Droit-Volet, 2018). Some researchers have instead focused on *passage of time judgements* (PoTJs), which assess the perceived pace of time rather than its duration (Droit-Volet & Wearden, 2016), to better capture the subjective experience of time and distortions in temporal experiences that might otherwise be missed. However, duration estimates, rather than PoTJs, dominate the existing literature, and research to date has included only a few experiments that examine both PoTJs and duration estimates (Droit-Volet, 2018).

Of the few empirical studies examining both PoTJs and duration estimates, it is unclear whether these two measures of time perception share common underpinnings, or if they are derived through separate cognitive mechanisms. For example, in intervals ranging from under two seconds (Droit-Volet & Wearden, 2016) up to 33 seconds (Droit-Volet, Trahanias, & Maniadakis, 2017), the two forms of judgement do not correlate, thus suggesting that these two types of time judgements are produced through separate underlying processes. When an interval is longer than this, however, Droit-Volet et al. (2017) found that PoTJs are predictive of duration estimation accuracy. This finding requires replication under controlled experimental conditions.

As it stands, this area of research possesses important empirical and theoretical gaps. Droit-Volet (2018) called for an investigation of different forms of time judgement (e.g., both duration estimation and PoTJs), across durations (ranging from a few seconds to several minutes). My thesis is a direct response to this call to action. The goal of my thesis was to test general models of human time perception by investigating the following broad research questions:

1) At what timescales do traditional models of time perception predict duration estimation performance?

2) Under what conditions are PoTJs and duration estimates related? And what factors moderate this relationship?

Answering these questions will help update widely used cognitive models in the area. Therefore, I will first review the literature on duration estimates and the most widely cited explanatory models underlying them in two common experimental paradigms (prospective and retrospective paradigms). I will then review the growing research on PoTJs. Throughout the literature review, I will address two key variables (task duration and task difficulty), which both influence the experience of time. This literature review will help situate a series of experiments that directly compared PoTJs and duration estimates while systematically manipulating the estimation paradigm, task difficulty, and task duration to investigate potential mechanisms driving psychological time distortions.

Part 1: Duration Estimation

The applications for studying alterations in the psychology of time are far-reaching. Our sense of time is necessary for understanding the temporal structure of speech (Wearden, 2008) and music (Rajendran, Teki, & Schnupp, 2018), narrative structure in episodic and autobiographical memory (Friedman, 2004), and phenomenological, rhythmic, and conceptual representations in the human mind (Michon, 2014). After all, time dictates most aspects of our lives. We use our sense of time to regulate our behaviour, to navigate, and to unify our experiences into a sense of continuity and consciousness (Montemayor, 2017) and to experience the psychological present (Block & Gruber, 2014; Fraisse, 1984; Michon, 1978). Yet the processes underlying our experience of time are only beginning to be clear, at least for short durations (Block & Gruber, 2014). Einstein once said that the “distinction between past, present, and future is only a stubbornly persistent illusion” (1955/1979), and decades of research have

added a psychological context to his claim. Early work on the psychology of time was published by Vierordt (1868; cited in Block & Zakay, 2018; Lejeune & Wearden, 2009) and later popularized by Fraisse (1963) and James (1890). An explosion of interest followed, and the expansion of research over the last few decades has led some authors to conclude that this area "has never been as exciting as it is at present" (Block & Grondin, 2014, p. 1).

The psychology of time is broad and multifaceted. The field is concerned with everything from the functioning of large-scale endogenous biological rhythms (e.g., the circadian clock) that oscillate over roughly 24 hours (Agostino, Bussi, & Caldart, 2018) to the much smaller psychophysical realm of human perception, occupying timescales of milliseconds to seconds. The latter focus aims to understand various cognitive processes (e.g., stimulus processing and decision-making; Klapproth and Wearden, 2011), and to map timing behaviour to neural correlates (see Table 1 of Teki, Griffiths, & Meck, 2014, for a summary). To situate this thesis in the broader literature, my research focused specifically on intervals ranging from half a minute to half an hour. This range was selected to better understand the cognitive processes underlying psychological time across a relatively neglected timescale in the literature, but one used for daily functioning. However, the experience of time and people's ability to report on it can be understood only by considering the complex interactions among several extraneous variables that influence that experience (Zakay & Block, 1997).

As an example, distortions of psychological time occur with the manipulation of a task's duration (e.g., Tobin et al., 2010), difficulty (Block et al., 2010; Polti, Martin, & van Wassenhove, 2018), and amount of attention directed toward time (e.g., Hicks et al., 1976). Several measures have been refined over the years to capture the slippery, illusory nature of psychological time and to map the experience of time onto a concrete and measurable variable

(Block and Gruber, 2014). Most approaches involve asking a participant to translate their experience of time into some sort of observable behaviour.

The outcome of interest in most of the literature on psychological time has been the precision of a *duration estimate* (sometimes called duration timing or a time estimate; Zakay & Block, 1997). For example, a person produces a behaviour for a specified length of time without counting or looking at a clock (production method; Zakay & Shub, 1998) or they recreate the duration that they just experienced (reproduction method; Block, Zakay, & Hancock, 1998). In reproduction, the participants might press a key to delineate the duration of a previously experienced stimulus (Mioni et al., 2016). Alternatively, they report the duration as a verbal estimate (e.g., by typing their answer on a keyboard; Tobin et al., 2010). In all cases, the person's estimate is compared with the time on a clock to determine their accuracy.

Additional methods are available for measuring psychological time when performing a task under *prospective* conditions. Under prospective conditions, participants *intentionally* monitor time throughout a task without an external timekeeping device. Figure 1 illustrates these prospective timing methods. Fewer options exist for experimenters who wish to measure *retrospective* estimation. In a retrospective condition, the experimenter presents the participants with a cover story of the experimental purpose (Block et al., 2018). Participants then estimate the duration of a task or event without having had the knowledge to keep track of time throughout the experiment. Their attention is thus assumed to have been directed to the non-temporal aspects of an experiment throughout the interval. Based on the accuracy of the participants' estimates, researchers can then measure how well time was *incidentally* encoded into memory. Ostensibly, methods for acquiring duration estimates of previously elapsed time are categorized as being either prospective or retrospective (Block, 1990; Block et al., 2018; Wearden, 2008).

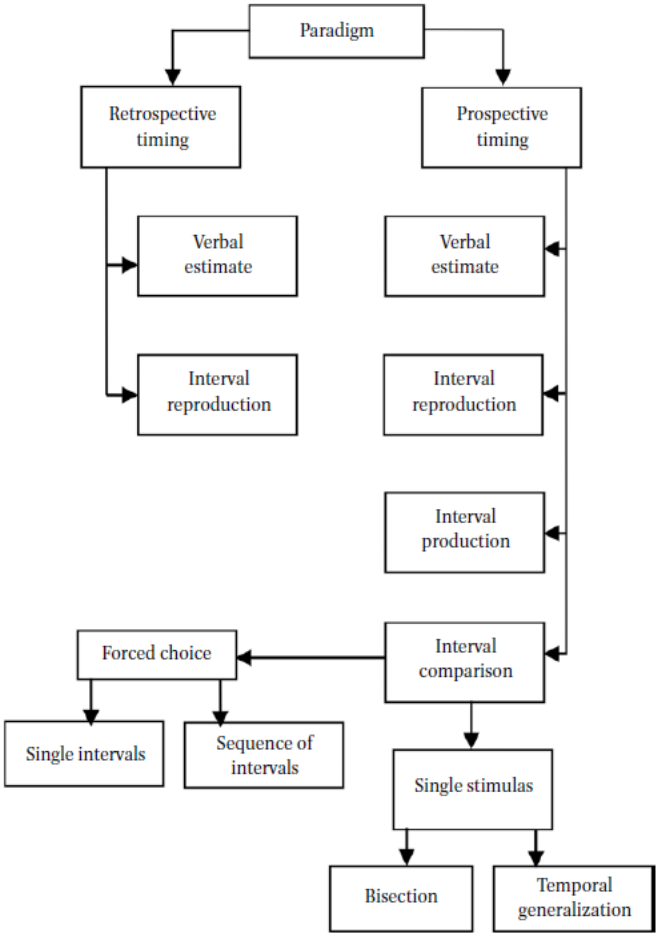


Figure 1. Summary of the main methods used for studying time estimation, adapted by Block, Grondin, & Zakay (2018) from the original depiction in Grondin (2010). Copyright 2018 by R. Block, S. Grondin, and D. Zakay. Licensed under CC BY-NC 3.0.

Prospective Duration Estimates

Separate cognitive processes are involved for intentionally and incidentally estimating time (Block & Gruber, 2014). In a prospective condition, participants actively attend to temporal information throughout a task. Relative to the retrospective paradigm, prospective duration estimates are assumed to rely heavily on the availability of attentional resources. The leading cognitive model of prospective time perception, the *Attentional-Gate Model* (AGM; Block & Zakay, 1997, 2008; Grondin, 2025; Zakay & Block, 1997), illustrates this theory (see Figure 2).

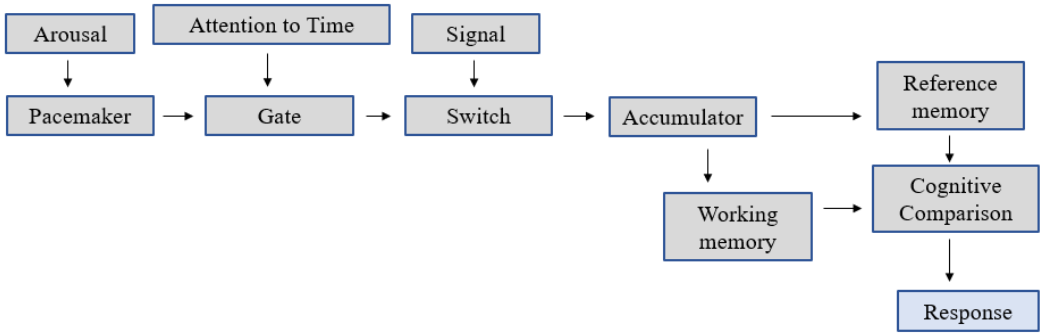


Figure 2. Attentional-Gate Model adapted from Zakay and Block (1997) and Grondin (2025).

Like a typical stopwatch, the AGM includes a pacemaker. Endogenous bodily processes, such as arousal, modulate this pacemaker. These processes generate "pulses" (rhythmic temporal information), which enter a cognitive counter (i.e., an accumulator) but only under specific conditions. That is, attention mediates this process by controlling a dynamic switch between the pacemaker and accumulator. The switch opens and closes depending on the amount of attention dedicated toward time (Zakay, 2014). Allocating more attention to time allows the system to accumulate more pulses (a mechanism known as the *attentional gate*). Conversely, when attention shifts away from timing, the gate closes, and fewer pulses accumulate. Therefore, perceived duration is assumed to reflect the total number of accumulated pulses (Block et al., 2018). This value is then compared with past events in memory, leading to an overall impression of time. An inaccurate accumulation of pulses thus creates a psychological time distortion.

Reference to an internal clock has dominated the literature (Droit-Volet, 2018; Michon, 2014). The endogenous clock-like mechanism has gained favour because it adequately describes time estimation performance under dual-task conditions. Specifically, when a secondary task is implemented in a prospective timing paradigm, perceived time shortens (Brown, 1997), and this "shortening" of time is exacerbated when the task is more difficult to do (Block et al., 2010). In

other words, with increased distraction and external demands, fewer pulses can be accumulated, causing a briefer perceived duration. This pattern of temporal distortion under dual-task conditions is not typically observed, however, under retrospective conditions.

Retrospective Duration Estimates

In retrospective conditions, participants are unaware that they will be asked to provide a duration estimate because they are instructed only to perform the secondary task. Early work on retrospective timing referred to this paradigm as a "remembered duration" (Wearden, 2016) because participants must draw on temporal information that was incidentally remembered during the interval. Any segments of the task that are especially memorable, or any changes in context/environment throughout the task, facilitate this process by serving as memory cues in retrospect. This theory is called the *contextual change hypothesis* (Block & Reed, 1978; Block & Zakay, 2008; Block et al., 2018). The more memorable the events of the interval, the longer the interval is estimated to be, because more information is available to call to mind upon at the interval's completion (Block & Reed, 1978; Block & Gruber, 2014; Tobin et al., 2010).

Retrospective estimates have received far less experimental attention compared to prospective ones (Tobin et al., 2010; Wearden, 2008). This lack of attention is probably due to the restrictive nature of this paradigm. As soon as the participant provides a duration estimate, the purpose of the experiment becomes clear, and any duration estimates thereafter will effectively be prospective (Block et al., 2018). Therefore, retrospective within-participant designs are simply not feasible.[1]

[1] Some researchers have attempted to investigate retrospective estimates by having participants perform multiple tasks and then estimate the duration of those tasks separately at the end of the experiment (thus achieving a within-participant design). Unfortunately, this method introduces several biases. Tasks at the beginning of the experiment, for example, tend to be judged to be longer than subsequent tasks (Block & Zakay, 1997). Moreover, each task is judged in relation to the others to arrive at holistic perception of the entire length of the experiment. In other words, duration estimates using this method are probably constructed using memory for entire sequence of intervals, not just the one in question (Block, 1978).

As mentioned, the number of available estimation methods is limited in retrospective conditions. Reproduction and verbal-estimation methods are typical of this paradigm because they both feature an encoding phase that does not require the participant to know about an impending time judgment. However, for lengthy tasks, reproduction quickly becomes unfeasible, as it doubles the time required for the experiment. Verbal estimates are thus more practical for retrospective designs (Block et al., 2018). Therefore, direct comparisons between prospective and retrospective paradigms often use a verbal estimation method (e.g., Bisson & Grondin, 2020; Bisson et al., 2012; Tobin & Grondin, 2009; Tobin et al., 2010; Walker et al., 2022).

The Effect of Cognitive Load on Prospective and Retrospective Estimates

Despite the limitations of retrospective designs, a cumulative picture of human duration estimation has begun to emerge (Block & Gruber, 2014), and researchers over the past 30 years have refined our understanding of how people perceive duration. In their seminal paper, Block & Zakay (1997) examined duration estimate performance across experiments using prospective and retrospective designs and found that prospective estimates were 16% greater on average than retrospective ones. This discrepancy in estimation performance is typically referred to as the *paradigm effect* (e.g., Bisson & Grondin, 2020). However, the cognitive load of the task moderates this effect.

Block et al. (2010) define cognitive load as the information-processing demands of a task. Therefore, throughout this thesis, “cognitive load” will be used with the same meaning. Block et al. (2010) conducted a meta-analysis that found that high cognitive load conditions diverted attention away from timing in the prospective paradigm, thereby shortening estimates. Conversely, such conditions appeared to increase the number of memorable cues in retrospective

paradigms. Instead of becoming shorter, retrospective estimates increased under heightened load, leading to the cross-over interaction shown in Figure 3.

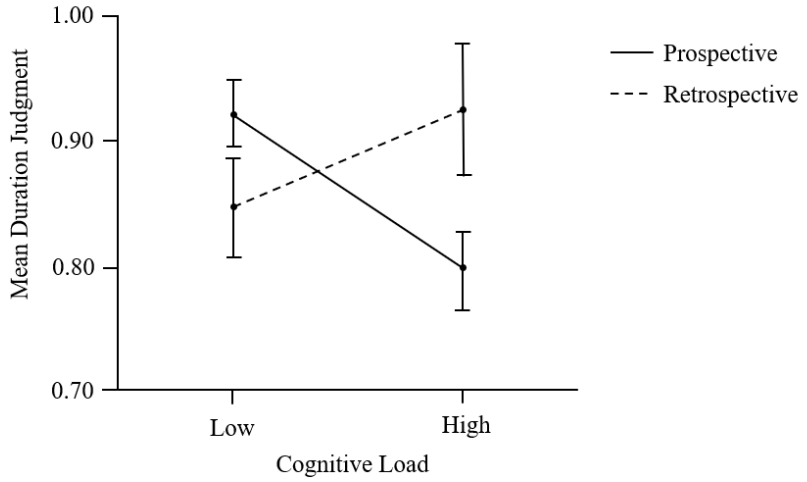


Figure 3. Interaction between estimation paradigm (prospective and retrospective) and cognitive load, adapted from Block et al. (2010). Mean duration judgement ratios represent participants' duration estimates relative to the actual task duration. A value of 1.00 indicates that participants accurately estimated the task's duration, while values below 1.00 indicate underestimation. Error bars are the standard errors of the mean.

Concurrent tasks in this area of research differ greatly from one experiment to the next. Block et al.'s meta-analysis depicting the strong interaction effect above included 117 experiments that combined six types of cognitive load based on the secondary tasks used across experiments (memory demands, processing demands, processing difficulty, attentional demands, response demands, and familiarity). The variability of tasks employed across experiments makes comparing estimation paradigms a challenge. To highlight this challenge, consider the mental effort required of passively watching a boiling pot of water (Block et al., 1980) compared to the more stimulating (and probably more enjoyable) act of listening to a piece of music (Brown & Stubbs, 1988; 1992). Consider now how these tasks differ from the attentional demands required of a Stroop task (Zakay & Fallach, 1984; Predebon, 1999), or from the memory and perceptual

demands required of memorizing and rehearsing lists of items (Miller, Hicks, & Willette, 1978) and tracing a star figure through a mirror (Kurtz & Strube, 2003).

To investigate the impact of cognitive load on duration estimates, it is necessary to manipulate the cognitive demands of a single task rather than compare duration estimate results across vastly different experimental conditions. This can be accomplished by manipulating the difficulty level of a single cognitive task. This manipulation is sometimes referred to as *workload* (Howard et al., 2020). Workload affects prospective estimation because the resources required to track time intentionally are limited. That is, the participant's limited attentional resources can be diverted away from time by tasks featuring a high workload (Brown et al., 2013). This *attention-allocation hypothesis* (Brown 1997, 2006) is at the heart of the AGM (Block, 2003). Fewer pulses can reach the accumulator when attention is diverted from the timing task (Gibbon et al., 1984), thereby shortening the perceived duration. However, investigations comparing prospective and retrospective estimates while manipulating the workload of a single task are based almost exclusively on studies of very short durations.

Task Duration: How Estimates Differ Across Timescales

As stated, comparing prospective and retrospective timing paradigms helps to define the role of intentional vs. incidental encoding of temporal information. Yet, as shown in Table 1, almost all experiments that have directly compared estimation paradigms have focused on tasks lasting two minutes or less. Fewer direct comparisons have been published investigating estimates over the span of two minutes.

Table 1.
Past direct comparisons between prospective and retrospective time estimation.

Experiment	Duration
120 seconds or less	
Avni-babad and Ritov (2003)	120 s
Boltz (2005)	7-10 s

Brown (1985)	16 and 32 s
Bueno Martinez (1990)	80 s
Gruber and Block (2003)	15 s
Hicks, Miller, and Kinsbourne (1976)	42 s
Klapproth (2007)	15-40 s
Kurtz and Strube (2003)	30 and 60 s
Martinelli & Droit-Volet (2022a)	20, 30, 45 s
McClain (1983)	120 s
Miller, Hicks, and Wilette (1978)	32-54 s
Predebon (1995)	10-50 s
Predebon (1996)	48 s
Predebon (1999)	12.5-50 s
Zakay (1992)	3 and 6 s
Zakay (1993)	12 and 15 s
Zakay and Fallach (1984)	10 s
121 seconds to 20 minutes	
Block (1992)	165 s (Exp. 1) 160 s (Exp. 2)
Block, George, and Reed (1980)	270 s
Brown and Stubbs (1988)	466 and 836 s
Brown and Stubbs (1992)	14.45-19.18 (Exp. 1) 7.7-19.6 min (Exp. 2)
Bisson, Tobin, and Grondin (2012)	14 min
Lim, Kum, and Lee (2015)	60 s – 20 min
Martinelli & Droit-Volet (2022a)	1.3 min, 2 min, 3 min
Kikkawa (1983)	20 min
Over 20 minutes	
Bakan (1955)	60 min
Bisson and Grondin (2020)	42 min
Tobin and Grondin (2009)	8 and 24 min
Tobin, Bisson, and Grondin (2010)	12, 35, and 58 min
Walker, Aswad, and Lacroix (2022)	8 and 58 min

Note. This table is an updated version of Table 1 presented in Tobin et al. (2010).

In this thesis, the term *long duration* will refer to conditions lasting longer than the typical "two minutes or less". Conditions lasting less than two minutes will thus be referred to as a "short" duration going forward.

A few of the long-duration direct comparisons between paradigms in the literature, duration was sometimes overestimated under prospective instructions (e.g., Tobin et al. 2010; Bisson et al. 2012), confirming the generalizability of the typical paradigm effect in longer

conditions. Other experiments of this length, however, found no such effect (e.g., Kikkawa, 1983; Tobin & Grondin, 2009), including the only experiment lasting one hour (Bakan, 1955). Additionally, Walker et al. (2022) found an effect of paradigm in the typical direction at eight minutes (with prospective estimates greater than retrospective ones), but no such effect was found at 58 minutes under identical experimental conditions. Overlapping cognitive processes that emerge under specific task conditions might explain the null effect of the estimation paradigm at 58 minutes.

In a selective review of the literature, Block and Gruber (2014) suggest that delaying prospective estimates may trigger the involvement of memory, making these conditions more like retrospective ones. Likewise, if the task is monotonous (as was the visual and memory search task in Walker et al., 2022), participants in a retrospective paradigm might begin to think about the passage of time. If this latter claim is true, then a paradigm effect should emerge when comparing a monotonous condition with a more challenging one.

Yet there is a paucity of research on the effect of workload on duration estimates in tasks longer than two minutes. To put Block et al.'s (2010) crossover interaction in perspective, a 60-second interval in their meta-analysis was considered "long", and their findings contrast with evidence from experiments investigating even longer durations. Tobin and Grondin (2009), for example, compared prospective and retrospective estimates at eight and 24 minutes under easy and difficult levels of a Tetris game. They found no effect of task difficulty on prospective and retrospective estimates. Walker et al. (2022) also found that the task's difficulty level did not affect participants' prospective or retrospective duration estimates when engaged in a visual and memory search task lasting either eight or 58 minutes. Therefore, further research is needed to

determine whether cognitive workload interacts with the estimation paradigm during a prolonged task.

If the cognitive load of a task is found to affect estimation performance only at short durations, but not at long ones, then there may be a moment when attention to time offloads in a prospective timing task. In other words, prospective time perception might not fit within an attention-allocation model (like the AGM) after a certain amount of time has elapsed. This proposed threshold, in which attention to time is offloaded, will be referred to as the *boundary of attentional release*. Perhaps timing is offloaded from the AGM onto other cognitive mechanisms better suited to long-duration time perception (e.g., memory) once this boundary is reached. Therefore, load effects are most likely to be observed at timescales in the range of seconds, when attention and working memory resources are shared between timing and a concurrent task. Durations longer than this may not be affected by the task's workload.

The effect of task duration on estimation accuracy. Although "the precise mechanism by which time is encoded in working memory is not yet understood" (Teki et al., 2017, p. 180), working memory structures are thought to be involved in remembering ranges of seconds to minutes. Anatomical structures for memory consolidation are thought to be involved in remembering sequences of events and contextual information via "time cells" in the hippocampus (Teki et al., 2017). Other structures are also involved in recalling timespans of seconds, minutes, and years (e.g., medial temporal structures; medial diencephalic structures; Blumenfeld, 2010). However, the complex reality is that temporal encoding is distributed throughout the brain (e.g., basal ganglia, cerebellum, prefrontal and parietal cortex, hippocampus), with neural overlap and flexible resource allocation contributing to how the brain represents time (Teki et al., 2017). In other words, specific brain structures may become involved

at different time scales in the formation of explicit memories of the interval. Estimating time probably becomes more complex when additional brain structures become involved as the experimental interval increases. Therefore, regardless of whether participants make their estimates prospectively or retrospectively, and regardless of the task's workload, the task duration itself is a significant and robust moderator of estimation performance.

Walker et al. (2022) found that task duration significantly affected estimation accuracy, regardless of whether participants were in a prospective or a retrospective timing condition. Estimation performance was measured by comparing the participants' estimated duration (E_D) with the actual task's duration (T_D). Their estimate is divided by the objective time to create an *estimation ratio*.

$$\text{Estimation Ratio} = E_D / T_D. \quad (1)$$

Ratios closer to one indicate more accurate estimates; those above or below one indicate over- or underestimation, respectively. By using an estimation ratio, participants' estimation accuracy is assessed relative to the magnitude of the estimated duration. The researcher can thus compare estimation accuracy across conditions of different lengths.

Across conditions, participants overestimated the task's duration in the eight-minute task (Mean estimate = 10.7 minutes, Median = 10 minutes; ratio of 1.34) and underestimated the 58-minute task (Mean = 42.5 minutes, Median = 40 minutes; ratio of .73). Before this experiment, Tobin and Grondin (2009) also found that participants significantly overestimated an eight-minute task on average (ratio of 1.44) and underestimated a 24-minute task (ratio of .80). Moreover, Tobin et al. (2010) reported a significant difference between their shortest task and their other two task durations. They found a higher ratio in their 12-minute task (≈ 1.5) compared to their 35-minute (≈ 1.1) and 58-minute (≈ 1.1) tasks. Droit-Volet et al. (2018) reported the same effect in an experience-sampling experiment in which they collected only prospective

estimates. Participants overestimated duration in almost all conditions, except when the target interval lasted longer than 24 minutes (see Table 2). Although no retrospective estimates were collected in the latter experiment, all the experiments outlined above showed the impact of task duration on estimation accuracy (i.e., ratios decrease with increased time spent on a task).

Table 2.

Duration Estimates in Droit-Volet, Monceau, Berthon, Trahanias, & Maniadakis (2018) with estimation ratios calculated.

2-8 minutes group			**8-32 minutes group**		
	Mean duration estimate	Estimation ratio		Mean duration estimate	Estimation ratio
2 minutes	2.67	1.34	**8 minutes**	12.21	1.53
3 minutes	4.03	1.34	**12 minutes**	16.48	1.37
4 minutes	5.90	1.48	**16 minutes**	20.05	1.25
5 minutes	6.63	1.33	**20 minutes**	21.51	1.08
6 minutes	7.64	1.27	**24 minutes**	25.15	1.05
7 minutes	10.32	1.47	**28 minutes**	26.19	0.94
8 minutes	10.40	1.30	**32 minutes**	26.79	0.84

Note. These verbal estimates were collected within a prospective timing condition.

Although internal clock models like the AGM are typically used to explain prospective estimation, the retrospective contextual change hypothesis might better accounts for the effect of task duration on estimation accuracy in long tasks. Context is presumed to change rapidly at the onset of an experiment (Hintzman, Block, & Summers, 1973), leading participants to judge the beginning of a task as longer. As the task duration increases, fewer memorable changes occur per unit of time (Wearden, 2016). Therefore, increasing the length of a task while holding all else constant should lead to a subjective shortening of time in retrospect (as supported by the results above). The moment at which duration estimates align perfectly with the actual task duration is called the *indifference point* and seems to be unique to each experiment (Eisler, Eisler, &

Hellstrom, 2008).[2] In other words, each experiment contains a point at which duration estimates are not distorted by extraneous factors. However, the task's duration likely affects more than just the accuracy of people's estimates.

The effect of task duration on estimation uncertainty. Some researchers suggest that participants have an awareness of temporal distortions within a task (Lamotte, Izaute, & Droit-Volet, 2012), including the magnitude and direction of their duration estimation errors (Akdoğan & Balcı, 2017). There has thus been a recent move toward measuring the subjective uncertainty of duration estimates by asking participants to provide a minimum and a maximum range in which they believe the task duration falls (e.g., Bisson & Grondin, 2020; Grondin & Plourde, 2007; Tobin, Bisson, & Grondin, 2010; Tobin & Grondin, 2012; Walker et al., 2022). This measure has taken on many names in the literature, including a "Weber's Fraction-like index", a "Relative Uncertainty index" or, for the present thesis, an "Internal Uncertainty" index (IU). The IU is calculated by collecting a maximum and minimum estimate from each participant and dividing the difference by the actual task duration. Like the estimation ratio, this measure adjusts for proportionality, allowing intervals spanning different timescales to be compared with one another.

$$\text{IU} = (Max_T - Min_T) / T_D. \quad (2)$$

Like estimation ratios, the task's duration also influences the IU index. For example, Walker et al. (2022) found that an eight-minute task produced greater uncertainty (i.e., a wider

[2] Within-subjects designs have been known to follow a similar pattern of over and underestimation at very short durations (in the range of milliseconds). When a single participant estimates a series of interval in a prospective paradigm, there is a central tendency effect in which their estimates begin to approach the mean of all the intervals combined (Murai & Yotsumoto, 2016). This is sometimes called *Vierordt's law*, which is defined by the tendency for longer intervals to be underestimated and shorter intervals to be overestimated within the same experiment (Brown & Stubbs, 1992; Woodrow, 1951). However, Tobin et al. (2010) and Walker et al. (2022) used between-subject designs. Participants could not have adjusted their responses based on previous experience because they only performed the task one time. Therefore, this over and underestimation effect must be driven by some other mechanism.

confidence range) compared to an identical 58-minute task. This finding replicated the only other study to assess IU at a 58-minute interval (Tobin et al., 2010). Walker et al. (2022) also found that the experimental paradigm moderated IU, with participants in the prospective condition showing a larger confidence range compared to those in the retrospective condition, but this effect was seen only in the eight-minute task (there was no paradigm effect on IU at 58 minutes). Tobin et al. (2010), however, did not find an interaction between paradigm and duration on IU. These findings suggest that the effect of duration on IU may vary across experimental contexts. Importantly, IU may provide information about the decision-making processes underlying duration estimation that is not captured by estimation ratios alone. This measure remains fairly underexplored.

The Need to Collect More Than Just an Estimate

To summarize, Part 1 of this chapter shows that direct comparisons between prospective and retrospective paradigms can inform contemporary models of human time perception. The current models (the AGM and the contextual change hypothesis of prospective and retrospective timing, respectively) are built on estimation performance in tasks spanning less than two minutes. These models predict that workload should influence duration estimates differently depending on the estimation paradigm (Block et al., 2018). However, the generalizability of these models to longer durations remains unclear. The point at which a task's workload no longer affects estimation accuracy (the boundary of attentional release) has yet to be established. There is thus a need to systematically manipulate task difficulty and duration while examining duration estimation performance (accuracy and uncertainty). This constitutes the first aim of my thesis.

In addition to this aim, I also aimed to address the limitations of the duration estimate itself. After all, duration estimates represent a translation process in which the psychological

experience of time is converted into a language-dominated convention (i.e., the standard units of minutes and seconds, Michon, 2014). In other words, verbal duration estimates reflect a decision process in which individuals must translate their experience of time into a reportable format. Although measures of uncertainty can provide insight into this translation process, stopwatch-like estimates (even when expressed as ranges) may not fully capture the full experience of psychological time, especially during prolonged tasks. The following section addresses this limitation by considering an alternative measure of temporal experience.

Part 2: Passage of Time Judgements (PoTJs)

The previous section of this thesis examined people's experience of time in prospective and retrospective duration estimation paradigms. In these paradigms, participants provide estimates of elapsed time upon completing a task, and researchers then use these estimates as proxies to infer whether a distortion has occurred (e.g., overestimation indicates that the duration was perceived as lasting longer than it was).

As an alternative method for measuring psychological time distortions, Wearden (2005) proposed a new type of time judgement, called *Passage of Time Judgements* (PoTJs). PoTJs do not require participants to use conventional units of measurement when communicating their experience. Instead, participants rate how "fast" or "slow" time felt like it passed, typically on a 7-point scale (e.g., Droit-Volet & Wearden, 2016). For example, while reading this paragraph, you are perhaps left with an impression of how fast or slow time is passing. This impression may or may not match the actual number of seconds you have spent on this section of this thesis, nor the number of seconds you would estimate if asked to do so. Instead, the internal pace of time involves introspection on the self in time (also known as *self-time*; Droit-Volet et al., 2018). It is

generally considered a phenomenological experience belonging to the domain of philosophers (e.g., Husserl, 1964). However, Droit-Volet (2018) highlights that researchers have recently begun to explore this experience experimentally.

PoTJs can be obtained from participants at the end of a task (Thönesa & Stocker, 2019). Researchers can thus gain insight into the pace of internal "subjective" time rather than comparing duration estimates with "more objective" (clock) time. In other words, instead of inferring the existence of a temporal distortion by examining how accurate their duration estimates were, researchers can simply ask people whether their perception of time *felt* altered. Like duration estimates, PoTJs do still reflect an internal process by which the person translates an experience of time into a rating. It is thus not completely appropriate to call these estimates "more subjective" (Wearden, 2016). Nonetheless, measuring PoTJs can yield novel insights into the experience of self-time, free from the pressure of guessing the duration correctly.

Prospective PoTJs

As discussed in Part 1 of this chapter, much of the literature on the psychology of time focuses on the workings of an internal clock (e.g., Treisman, 1963; Buhusi and Meck, 2005). However, contrary to what one might assume, the pace of self-time in a task is not necessarily predictive of duration estimation accuracy (Droit-Volet & Wearden, 2016; Droit-Volet & Dambrun, 2019; Droit-Volet et al., 2017), and thus the functioning of that "clock".

For example, in an experiment by Droit-Volet and Wearden (2016), participants received several alerts each day on a mobile device, prompting them to judge the duration of a stimulus that could range from 350 ms to 1650 ms. They were instructed to base their estimates on a range of 100–2000 ms. After providing an estimate, they indicated how fast time was passing for them at the moment of the alert, on a 7-point scale. Verbal estimation in this experiment did not vary

with PoTJs, highlighting a potential disconnect between PoTJs and estimation accuracy. Subsequent investigations comparing duration estimates with PoTJs have since concluded that PoTJs do not depend on the raw material used to arrive at a duration estimate (i.e., internal clock pulses; Droit-Volet & Dambrun, 2019). Rather, PoTJs appear to rely on mechanisms distinct from those of prospective estimation.

Retrospective PoTJs

PoTJs also show dissociation from retrospective estimates. Wearden (2008) found that these two types of time judgements are affected differently by the complexity of a task. In this experiment, retrospective PoTJs and duration estimates were collected from participants who watched video clips under two conditions: passive viewing or counting character interactions. Although participants judged that the shorter clips passed more quickly than the longer ones, participants retrospectively overestimated the duration of the shorter clips relative to the longer ones. This pattern is notable because the conditions that were judged as "faster" were overestimated. This result is counterintuitive, as one would expect that "fast" conditions would be *under*estimated. These findings demonstrated a clear dissociation between PoTJs and retrospective duration estimates, as they trended in opposite directions.

Notably, in Wearden's (2008) experiment, the amount of information processing required of participants while watching the clip only influenced the PoTJs. As shown in Figure 4, retrospective duration estimates were similar regardless of whether participants were actively or passively watching the film clips, whereas PoTJs varied according to information-processing demands. Specifically, when participants reported time as passing quickly, increased processing demands made time feel slower. Conversely, when participants reported time as passing slowly, increased processing demands made time feel quicker (Wearden, 2008).

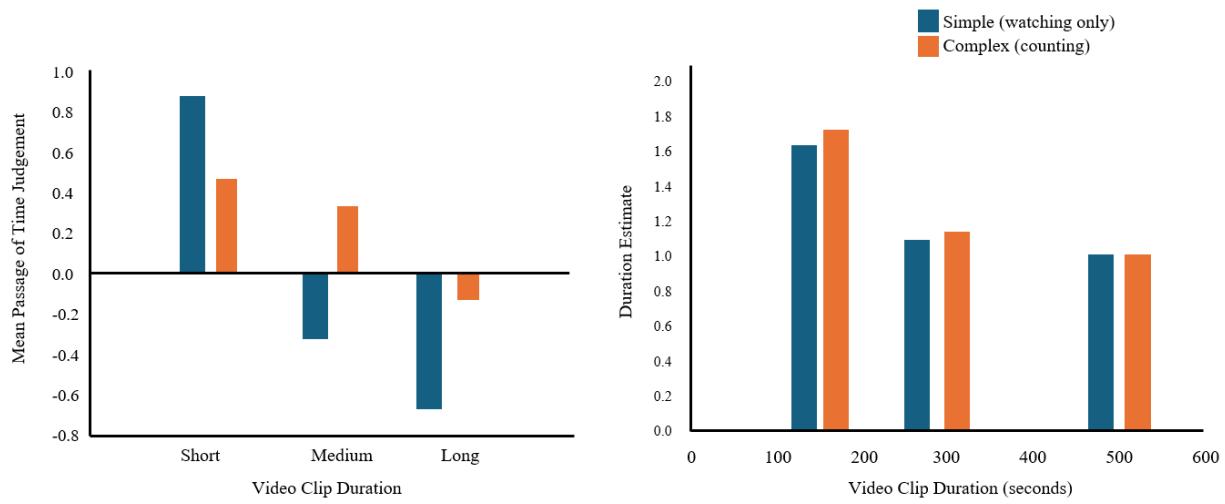


Figure 4. Results adapted from Wearden (2008). Left panel: Positive values indicate that time was judged as passing faster than normal, negative values indicate that it is passing slower than normal. Right panel: Retrospective duration estimates divided by the real duration (Estimation ratio; a value of 1.0 indicates accuracy).

Not only are the retrospective results reported in Wearden (2008) contrary to what one would expect from a contextual change model (active processing should create more contextual cues, leading to overestimation), but they also highlight how collecting only a duration estimate might miss information about the participants' experience of time. Although the demands of the task did not affect duration estimates, the PoTJs indicated that the task did in fact distort psychological time. The duration estimates thus failed to capture fluctuations in the experience of time in response to changes in processing demands.

Unfortunately, experiments investigating the relation between retrospective estimates and PoTJs are rare. Instead, most of the direct comparisons between duration estimates and PoTJs occur in prospective paradigms to capture time perception in everyday circumstances.

The Effect of Cognitive Load on PoTJs

Capturing time perception in daily life is most often accomplished using an experience-sampling method (e.g., Droit-Volet & Dambrun, 2019; Droit-Volet & Wearden, 2015; Droit-Volet et al., 2018; Droit-Volet et al., 2017). For example, participants might provide estimates

and PoTJs over several days using a mobile device, sometimes resulting in as many as 40 data-collection periods per participant (Droit-Volet & Wearden, 2016).

Droit-Volet et al. (2017) found inconsistent results across two similar experience sampling experiments. In their first experiment, no correlation was found between the difficulty level of the activity and PoTJs, whereas in their second experiment, the researchers did find a significant correlation. One key difference between these two experiments was the duration of the interval being judged (experiment 1 examined shorter durations). Additionally, Droit-Volet et al. suggest that the "inconsistency of the data is certainly due to the great variability in activities performed by individuals in everyday life" (p. 120). Like duration estimates, what we know about PoTJs comes largely from varying circumstances that add noise to the results.

To address task variability across experiments, my master's thesis work at Carleton University (Walker, 2019) collected exploratory data about the passage of time. Although this work primarily focused on comparing prospective and retrospective duration under varying levels of cognitive load (high vs. low) and across task duration (eight vs. 58 minutes), an exploratory component of the master's thesis examined PoTJs as well. After having subsequently published the planned analyses (see Walker et al., 2022), there still remain unpublished exploratory results from this experiment that warrant follow-up and further investigation.

The results of a controlled direct comparison. My master's thesis found a surprising null effect of cognitive load (defined as "task difficulty") in a visual and memory search task on the accuracy and uncertainty of people's duration estimates at eight and 58 minutes. Yet, the cognitive load of the task did influence their PoTJs at both time scales (p = .002; Walker, 2019). Overall, participants reported that time passed faster during the eight-minute task than it did during the 58-minute one. Moreover, at eight minutes, participants reported that time passed

more slowly when the task was easy (p = .02). Therefore, the cognitive load of the task seems to have influenced the measured experience of time differently depending on the type of time judgement requested by the experimenter (duration estimate vs. PoTJ).

Are we measuring cognitive load or cognitive engagement? Recall that in the AGM model of prospective duration estimation, high workload conditions take attention away from the timing task, leading to fewer temporal pulses reaching the mind's accumulator. The AGM thus reliably predicts estimation performance in prospective conditions at very short durations (e.g., Brown, 1997; Brown et al., 2013). Conversely, the contextual change hypothesis predicts that, when judging a duration in retrospect, high-load conditions lead to overestimation (e.g., Block et al., 1997). Neither of these frameworks accounts for the impact of cognitive load on PoTJs. Indeed, there is reason to speculate that cognitive load only affects PoTJs *indirectly*.

As part of exploratory data collection, Walker (2019) asked participants to rate their boredom and engagement levels during a visual and memory search task. It was found that the cognitive load of the task significantly impacted PoTJs (p = .01), but that adding boredom and engagement ratings to the regression model in a second step (alongside cognitive load) eliminated cognitive load's effect on PoTJs (p = .60). Figure 5 depicts an exploratory mediation model used to further interpret that data. This model highlights how cognitive load exerts an indirect effect on PoTJs by influencing levels of engagement and boredom.[3]

[3] Engagement and boredom were treated as two separate variables and not opposite ends of a continuous variable. This is because a person could theoretically be fully engaged in a task (e.g., a repetitive visual and memory search task that requires controlled attention) yet find the task subjectively boring. In Walker (2019) engagement and boredom rating were correlated at r = -.44.

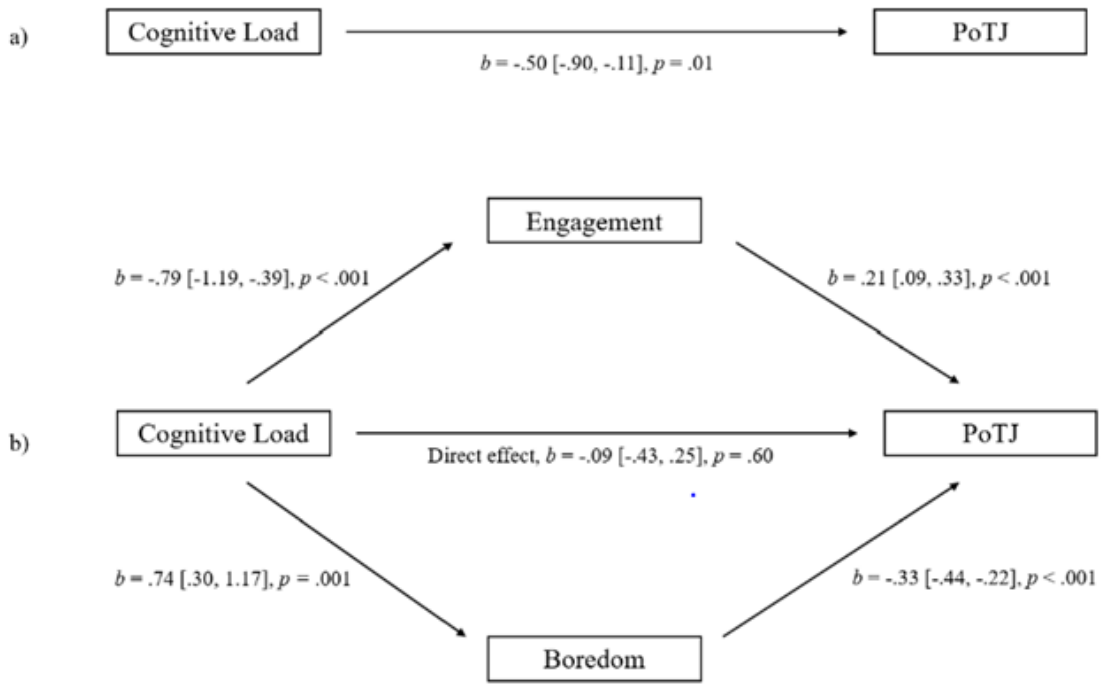


Figure 5. Model reproduced from Walker (2019). Complete mediation model: a) the total effect of cognitive load on PoTJs; b) the indirect effect of cognitive load on PoTJs through engagement and boredom. Engagement and boredom were correlated at -.56.

The effect of boredom on PoTJs is not surprising. Affective states such as sadness, arousal, and boredom have been shown to predict PoTJs in past research, with boredom a consistent predictor across experiments (Tanaka & Yotsumoto, 2017). Correlations between engagement and PoTJs have also been reported in the literature (e.g., Larson & von Eye, 2006). It is thus not "cognitive load" per se that influences the pace of time, but rather the affective appraisal of the experience that accompanies tasks of varying difficulty.

In fact, the rate of time passage increases under negative emotional states (Droit-Volet et al., 2013; Fayolle et al., 2015; Lake, 2019). The experience of time is thus dynamic, depending on how a person feels about the activity they are engaged in. The person's ability and interest in the activity, for example, are thought to be essential features in altering self-time (Larson, 2004). An optimal match between skill, interest, and challenge creates a sense of timelessness. This

sense of timelessness is one of the dimensions that characterize a state of flow (being "in the zone"; Hancock et al., 2019; Csikszentmihalyi, 1990), in which attention and action qualitatively merge and attention to time fades (Csikszentmihalyi, 1988; Csikszentmihalyi & LeFevre, 1989; Larson & von Eye, 2006). Alternatively, *protracted duration* is a term used to describe a circumstance in which the experience of time seems longer than clock time (Flaherty, 1991, 1993).

The indirect effect of cognitive load on PoTJs could explain why duration estimates and PoTJs seem to rely on "separate mechanisms." While the availability of attentional resources alters the accuracy of the prospective internal clock, and the availability of contextual cues alters the accuracy of retrospective temporal memory, PoTJs are instead altered by qualities of the activity that influence a person's depth of boredom or engagement (e.g., DOiT model; Larson & von Eye, 2006).

In conclusion, the AGM and the contextual-change hypothesis proposed to explain prospective and retrospective duration estimation do not fully explain alterations in the experience of time. To more accurately understand distortions in temporal experience, we must account for PoTJ data. Therefore, we must first review the relationship between PoTJs and the estimated durations in prolonged durations.

Task Duration: Comparing PoTJs to Duration Estimates Across Timescales

As stated, in their first experiment, Droit-Volet et al. (2017) found no relation between PoTJs and verbal duration estimates. However, the target durations in this experiment only spanned several seconds. In a follow-up experiment investigating the two forms of time judgement at several minutes (i.e., between two and eight minutes), the researchers found a significant positive correlation, suggesting that duration is an important moderator of the

relationship between PoTJ and duration estimation. In fact, in a subsequent experience-sampling experiment, participants estimated durations ranging from two to 32 minutes (Droit-Volet et al. 2018). The best predictor of prospective estimation accuracy across conditions was the participants' PoTJs. Specifically, the target duration was judged as shorter when participants reported that time passed faster, and vice versa.

Contrary to Droit-Volet et al. (2018), participants in Walker (2019) rated the 58-minute task as passing significantly more slowly on a 7-point scale ($M = 2.5$) compared to the eight-minute task ($M = 4.1$). Yet, participants overestimated the shorter condition while underestimating the longer one. This over- and underestimation resulted in a significant correlation between PoTJs and duration estimates, in which participants overestimated the condition they reported as passing quickly (rather than underestimating the fast-paced condition, as observed in Droit-Volet et al., 2018). This intriguing result aligns with the shortest condition reported in Wearden (2008), in which overestimation occurred even though time passed subjectively quickly. Why would participants report time as passing quickly but overestimate the tasks' duration, and vice versa?

Rather than duration estimation and PoTJs being independent from one another, these two forms of judgement may be affected by the task's duration, although not necessarily in the same direction. Clearly, under some conditions, people experience time as passing slowly, yet they underestimate the task's duration (Walker, 2019). For example, if someone is aware of potential distortions in their experience of time during long, boring tasks, they might attempt to adjust their responses accordingly. In fact, Lamotte, Izaute, & Droit-Volet (2012) found that having an awareness of time distortions moderated the accuracy of people's duration estimates. Therefore, follow-up investigations are needed to confirm the association between PoTJs and

duration estimates at long durations, and to test whether the pace of time is considered by participants when formulating their duration estimates.

Part 3: Bringing it All Together

In a review article, Matthews and Meck (2014) chose the title "Time Perception: The Bad News and the Good." This title is an apt description of the contemporary research in this area. Although time perception is a field that has been extensively researched and elaborated (Block & Grondin, 2014), there remain several obstacles toward a unified model of time perception.

To summarize this first chapter, researchers typically collect duration estimates with a focus on very short task durations (Block & Zakay, 1997). To date, few direct comparisons have been conducted to test contemporary models of time perception across prospective and retrospective paradigms lasting several minutes (Tobin et al., 2010). Moreover, the literature in this area has mostly provided insight into the translation process whereby people convert an experience of time into commonly referenced units (i.e., clock time). This clearly formalized, language-dominated process (Michon, 2014) fails to encompass the quality of the experience (e.g., the pace of self-time). After all, common colloquialisms allude to distortions in a qualitative speed, pace, or movement of time (e.g., "time slowed down," "stood still," "flew by"). Yet it remains unclear whether the subjective pace of time affects the accuracy or uncertainty of a duration estimate (Droit-Volet & Wearden, 2016). At the very least, results are inconsistent (Tanaka & Yotsumoto, 2017). At the very least, the duration of a task appears to influence both measures of temporal experience. To account for this observation, Droit-Volet et al. (2018) thus proposed a new theory of time judgements for long durations to explain temporal experiences in prolonged tasks, depicted in Figure 6.

Cognitive Mechanisms for the Experience of Time at Long Durations

In the theory of explicit time judgements at very long durations, a clock-like mechanism keeps track of time in intervals that span several seconds. Information processing depends on short-term and working memory systems, as does processing time-related information as well (Droit-Volet et al., 2018). These systems have a capacity limit (approximately 15-30 seconds), which can be increased through rehearsal (Baddeley, 2000). When the task lasts longer than several seconds, however, additional mechanisms are proposed to account for the experience of time. A prolonged task is thus composed of smaller encoding periods (i.e., local intervals) that span the entire duration.

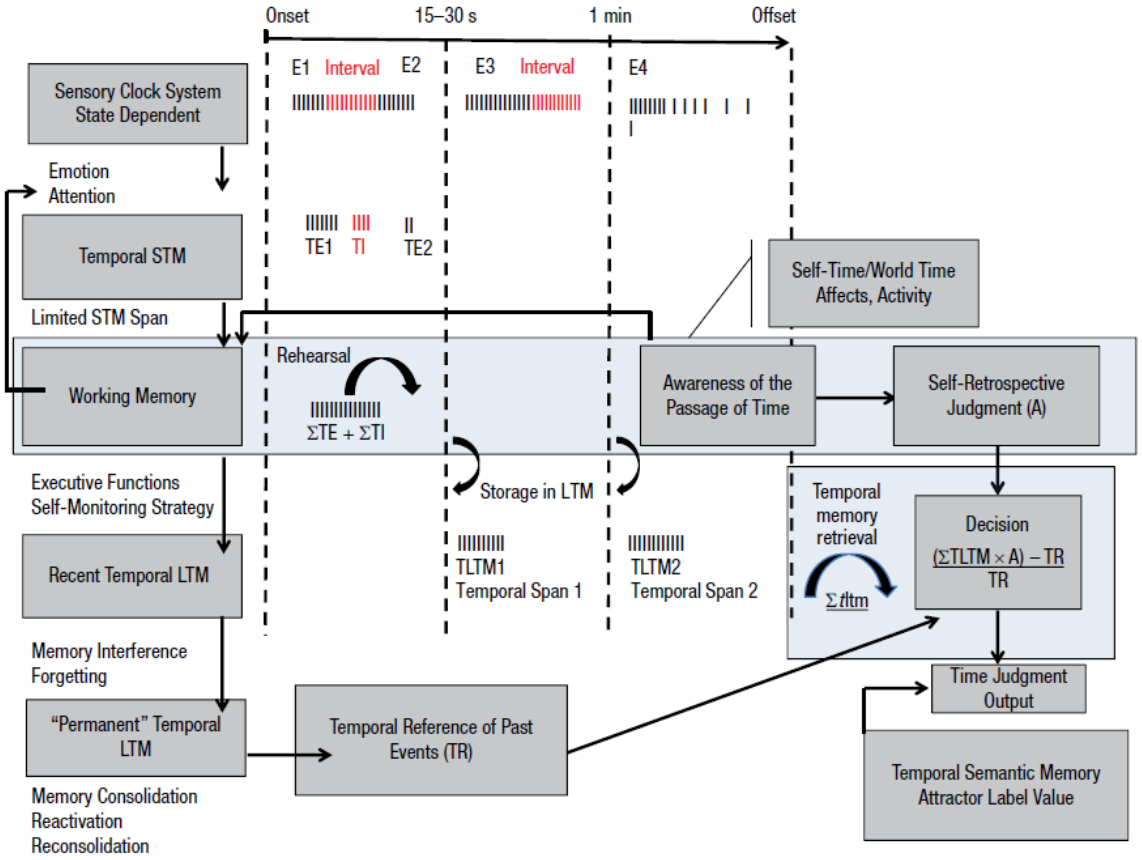


Figure 6. Model of explicit time judgments of very long durations reprinted from Droit-Volet et al. (2018). E = event; LTM = long-term memory; STM = short-term memory; TE = timing of event in number of pulses; TI = timing of temporal interval; TLTM = time in long-term memory. Copyright 2018 by S. Droit-Volet et al. Licensed under CC BY 4.0.

Non-temporal aspects of a task are used to delineate local intervals in memory, much like the cues proposed by the contextual change hypothesis. In fact, contextual factors help integrate events into a coherent whole or separate them in memory when reflecting on the interval (Clewett et al., 2011). Therefore, clock models like the AGM may explain the timing of local intervals which fall within working memory capacity, but contextual factors are critical for the timing of prolonged durations which require integration in memory, even in prospective paradigms.

A key element of Droit-Volet et al.'s theory is that the timing of long durations cannot simply be reduced to the two popular frameworks (the AGM or contextual change). That is, long durations are not timed solely by the accumulation of internal pulses, nor can estimates be reduced to the number of cues recalled at the end of the task. Instead, awareness of the passage of time plays a crucial role in the formulation of an estimate, particularly at the level of decision-making. Specifically, estimates increase or decrease as a function of awareness of the *speeding up* or *slowing down* of subjective self-time. This pace of time is a result of affective (e.g., boredom) and task-specific qualities (e.g., task difficulty). Thus, the participant performs an introspective analysis when asked to judge the duration of a task. In other words, people have representations in their long-term memory of what several minutes *feel like*. They compare the passage of time with prior experiences to arrive at "a symbolic representation of time in the form of minutes and seconds" (Droit-Volet et al., 2018, p. 13).

Building on Droit-Volet et al.'s (2018) theory, the AGM may appropriately describe estimation performance in tasks ranging up to 30 seconds. At such timescales, estimates are affected by the task's workload, as is typically found (Block et al., 2010). However, when the duration of a task exceeds working memory capacity and thus surpasses the boundary of

attentional release, local intervals are encoded and consolidated in long-term memory. Likewise, when no instructions are given to pay attention to time (retrospective condition), an estimate is formed from these contextual cues in memory, as has been suggested in past research (Block & Reed, 1978; Block & Zakay, 2008; Block et al., 2018). Taken together, how the approach to time estimation differs depends not only on the estimation paradigm (prospective or retrospective) but also on the length of the activity.

Adjusting Estimates to Account for the Pace of Time

If the estimation paradigm is retrospective, or if the task exceeds the boundary of attentional release, I hypothesized that several mechanisms would be involved in the formulation of a verbal duration estimate. One key component is the influence of PoTJs on duration estimation in lengthy tasks.

As mentioned in Part 1 of this chapter, the simplest interpretation of the contextual change hypothesis is that events with more changes are more memorable, leading to longer retrospective estimates. For example, in a stable context where there are few changes, participants later estimate that two stimuli occurred closer together in time compared to a situation in which there were many contextual changes between the stimulus presentations (Ezzyat & Davachi, 2014). In other words, even if two events occur at the same time points in the experiment, the condition with more contextual changes leads to the feeling that more time has elapsed between those two events.

As suggested by Droit-Volet et al. (2018), people probably become spontaneously aware of the passage of time when a task lasts longer than one minute, and task qualities that alter a person's affective appraisal of the experience accelerate or decelerate the passage of time at this time scale. Clewett, DuBrow, and Davachi (2018) provide a pertinent example of someone

recalling “a torturous commute to work as taking much longer than simply eating breakfast in their living room, even if the actual duration of these events was the same” (p. 162).

Task-specific features influence PoTJs because people experience time as passing more quickly or slowly depending on both their appraisal of the task *and* changes in context. When subsequently providing a duration estimate, individuals may attempt to compensate for this subjective experience of time. In some monotonous contexts, however, this compensation may overshoot. For example, Walker (2019) found that participants in a 58-minute task reported that time passed slowly, yet they substantially underestimated the duration of the task (M = 42.5 minutes). This finding suggests that participants perhaps over-corrected for their subjective experience when translating it into a duration estimate. This overcompensation could explain why the cognitive load of the task affected PoTJs but not duration estimation accuracy or uncertainty in Walker (2019).

In conclusion, the decision process underlying a duration estimate perhaps incorporates the subjective appraisals of time, particularly in prolonged tasks where the pace of self-time is more salient. One of the primary objectives of this thesis is to test this theory. I thus designed three experiments aimed at addressing this goal. These experiments directly compared duration estimation performance (accuracy and uncertainty) to passage of time judgments (PoTJs) across tasks of varying lengths and estimation paradigms. A systematic manipulation of task difficulty was accomplished by varying the task’s information-processing demands in two experiments. In addition, I examined changes in engagement and boredom as a function of task duration and difficulty, along with other subjective appraisals, to better understand how task features relate to both duration estimation and PoTJs.

CHAPTER 2: THE EXPERIMENTS

In all three experiments of this thesis, participants performed the same visual and memory search task in which they were instructed to search for targets among distractors on a computer screen. This task consistency allowed me to compare duration estimation and PoTJs across experiments, without introducing the additional variability that comes with altering the concurrent task. I selected a visual and memory search task to manipulate information processing demands via stimulus-response mapping.

Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977) formulated their theory of controlled versus automatic information processing when they first introduced the stimulus-response mapping technique. In this technique, experimenters assign participants to one of two task configurations. In the easy configuration, participants consistently search for the same memory targets among the same distractors on screen. Participants thus always provide a "target present" response on the keyboard to specific characters in the search array. This configuration of targets is called a *consistent mapping* condition. In this condition, visual searches quickly become automatic.

Alternatively, by shuffling the targets and distractors on every trial, participants cannot form a one-to-one relation between specific characters and keyboard responses. This configuration is a more difficult, *varied mapping,* condition. Controlled processing is required in this condition to ignore interfering information from the previous trial and thus select the appropriate keyboard response.

The relationship between stimulus-response mapping and automatic processing has been extensively studied in visual search paradigms (e.g., Hélie & Cousineau, 2011; Lefebvre, Cousineau, & Larochelle, 2008; Moors & De Houwer, 2006). To further differentiate controlled

and automatic processing, Cousineau and Larochelle (2004) found that performance is facilitated when searching for a target category among distractors from another category (e.g., searching for letters among digits). The above manipulations create an especially low cognitive load (or easy) condition (consistent mapping *and* consistent categories) and a high cognitive load (or difficult) condition (varied mapping *and* varied categories).

As a concurrent task, the visual and memory search task is also ideal because performance indices can be used to test whether the workload manipulation was successful. When the load is low, response times (RTs) should be significantly faster, and accuracy should be significantly higher than in a high-load task (e.g., Walker et al., 2022). In past research, manipulation checks are not always reported (e.g., Tobin & Grondin, 2009). To ensure that the difficulty levels were significantly different from each other, I performed manipulation checks before analyzing the time perception results in my experiments.

Another advantage of the visual and memory search task is that stimulus-response mapping yields relatively stable processing demands over time. As shown in Figure 7, performance plateaus in each condition within a few trials. Although there is some improvement in accuracy at the beginning of the task, participants in the varied mapping condition never reach the performance seen in the consistent mapping condition, regardless of the time spent on the task. Thus, any changes in the effect of task difficulty on time estimation performance must be due to changes in the processing mechanisms underlying psychological time, rather than to changes in task difficulty with practice.

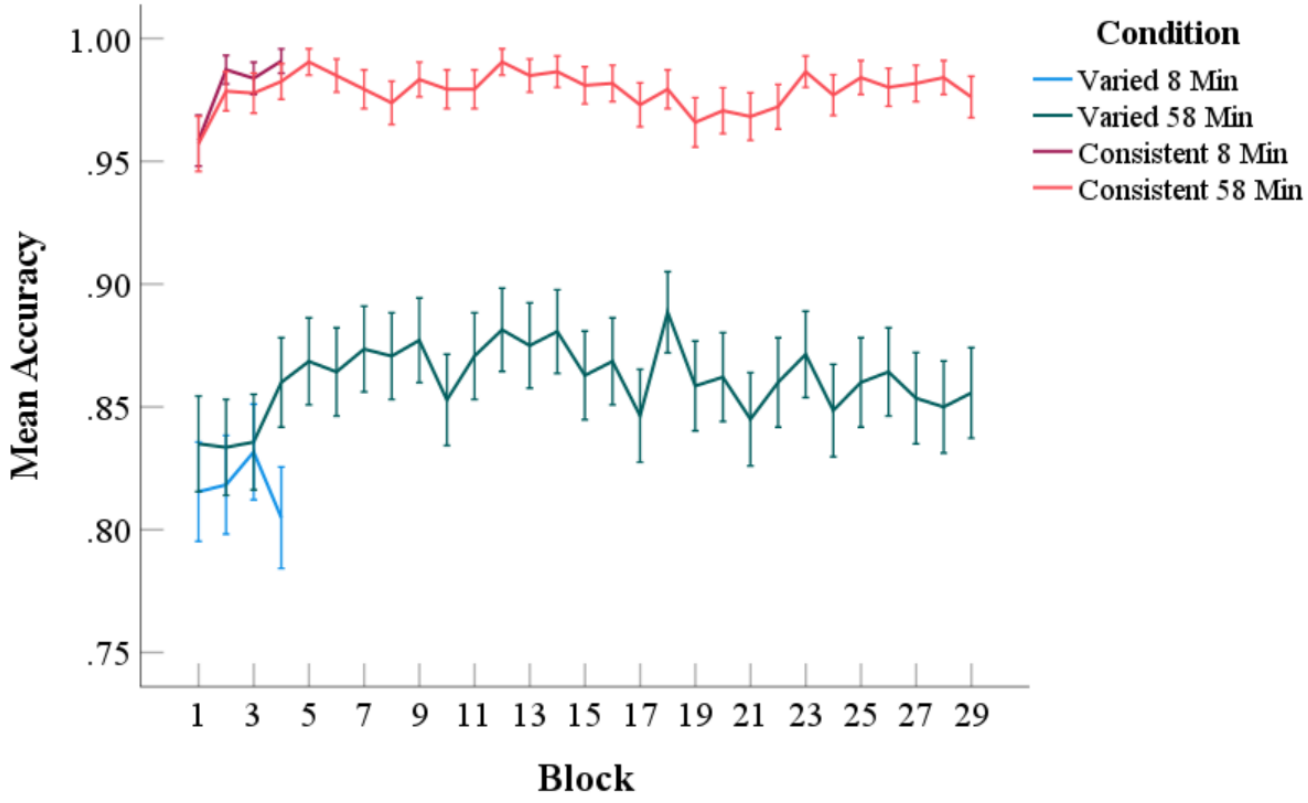


Figure 7. Accuracy in the Visual and Memory Search Task using data collected in Walker (2019), displayed by trial according to condition. Each block contains 20 trials, with clear differences between consistent and varied mapping conditions, even after 58 minutes of practice on the task. Error bars show the 95% confidence intervals of the mean.

Finally, with both letters and digits included in the memory sets (targets) and search arrays (targets and distractors, or just distractors), keeping track of time by counting would be incredibly difficult while also achieving good performance on the task. This task was thus ideal for measuring time perception in the three experiments explained next.

Using a visual and memory search task, Experiment 1 aimed to test the boundary of attentional release by comparing prospective and retrospective estimates across durations (30 seconds, one minute, two minutes, and four minutes) while varying the difficulty of the task. By varying both task difficulty and task instruction (prospective vs. retrospective), this experiment examined the roles of attention and workload on measures of time perception. The outcome

measures of interest included both the accuracy and the uncertainty of duration estimates provided by participants at the end of their task. In addition, I examined PoTJs, engagement ratings, and boredom ratings to test whether the relationship between PoTJs and duration estimates changes across timescales and how those PoTJs relate to internal affective states.

Experiment 2 then explored other factors that participants might consider while formulating a duration estimate and a PoTJ. I included variables that have rarely been explored in past research, such as *perceived* task difficulty (regardless of task assignment), the novelty of the task, how fun it was, how capable the participant felt during the task, and how distracted they felt during the task. Using only a prospective condition, I once again manipulated the task's difficulty and the task's duration. Crucially, rather than including brief durations such as 30 seconds or 1 minute, I implemented four longer durations (four, eight, 16, and 32 minutes). I thus aimed to investigate the relationship between duration estimate accuracy and PoTJ across four prolonged task durations at two difficulty levels.

Experiment 3 then put the relationship between PoTJs and duration estimates to the test. Rather than correlating these two dependent variables after manipulating factors such as difficulty and task duration, this experiment deliberately drew participants' attention to the pace of time before they provided their duration estimate, but only in half the sample. I chose this experimental design to directly assess whether attention to the internal sense of time passing influences people's estimates. I used both timing paradigms (prospective and retrospective) in this experiment to investigate the interplay between "attention-to-time" and "attention-to-the-subjective-pace-of-time". This final experiment aimed to test whether people compensate for the subjective pace of time when providing estimates in longer tasks, and thus whether PoTJs add explanatory power to the duration estimation performance at long durations.

Experiment 1: Testing Contemporary Models Across Time

Experiment 1 tested the internal clock model (AGM) and the contextual change hypothesis across varying task durations. I replicated the methodology used in Walker et al. (2022). I predicted that I would find a cross-over interaction between the estimation paradigm (prospective vs. retrospective) and cognitive workload (difficult vs. easy task; hereafter referred to as "task difficulty") in the shortest condition, as was reported by Block et al. (2010). However, I predicted that attention to time would be offloaded as task duration increased, and memory would prevail as the main mechanism for estimating duration when a task spans several minutes. Increasing duration would thus lead to an attenuated effect of task difficulty on estimation accuracy. This experiment thus systematically manipulated task difficulty while directly comparing prospective and retrospective duration estimates.

Furthermore, I collected ratings of engagement and boredom from participants, along with PoTJs, at the end of the experiment. Collecting this data helped determine whether engagement and boredom ratings affect PoTJs across time scales ranging from 30 seconds to several minutes. This experiment is also one of the few to investigate PoTJs using a retrospective paradigm (e.g., Wearden, 2008).

Experiment 1 Research Questions and Hypotheses

Q1: At what timescale does task difficulty (i.e., heightened information processing load) impact the accuracy and uncertainty of a duration estimate? If an effect is observed, is it in the expected direction according to the AGM and contextual change hypothesis?

H1: I predicted that heightened task difficulty would decrease (shorten) prospective estimates and increase (lengthen) retrospective estimates (like the cross-over effect observed in Block et al., 2010) at 30 seconds, suggesting that contemporary cognitive models of time

perception are effective at predicting the results of duration estimation at this time scale. As such, 30 seconds could be considered a "local interval", belonging to the realm of traditional timing processes. In conditions lasting longer than this, I expected the task's difficulty *not* to be a significant moderator of duration estimation performance in either paradigm.

Q2: Do ratings of engagement and boredom relate to PoTJs across various durations?

H2: I predicted that there would be a positive correlation between engagement (and a negative correlation between boredom) and PoTJs, but only in conditions lasting longer than one minute. This one-minute timescale is presumably when people become spontaneously aware of the passage of time (Droit-Volet et al., 2018) and begin to appraise the activity.

Experiment 1 Method

This experiment was a collaboration between researchers from the laboratory of Dr. Guy Lacroix at Carleton University and from the laboratory of Dr. Denis Cousineau at the University of Ottawa, with me as primary investigator across both sites. Recruitment began at Carleton University in October 2019 with the help of four volunteer research assistants, but we temporarily paused the experiment in the spring of 2020 due to COVID-19. Recruitment resumed collaboratively between the two universities in the Fall semester of 2022, when in-lab experiments were deemed safe to resume by both sites. There was also a slowdown in data collection in 2023/2024 during my maternity leave. The data collection period for this experiment thus spanned 5.5 years.

For this experiment, I replicated the methodology used in Walker et al. (2022). However, instead of replicating their eight- and 58-minute durations, the AGM and contextual change model were tested by examining the effects of task difficulty and the estimation paradigm at various durations, including a short one (30 seconds). As such, the task lasted either 30, 60 (one-

minute), 120 (two minutes), or 240 (four minutes) seconds. I chose these durations to help identify the moment at which task difficulty no longer affects duration estimation. Furthermore, PoTJs were collected from each participant, as well as engagement and boredom ratings, to follow up on the exploratory investigation of these three variables from Walker (2019).

Participants. In Block et al. (2010), the interaction between cognitive load and estimation paradigm on ratio results (estimation accuracy) was significant at $p = .001$. They found an effect size of $d = .40$ for this interaction. Using G*Power (Faul et al., 2007), 80% power to detect this interaction would require approximately 200 participants. In Walker et al.'s (2022) experiment, there was no effect of task difficulty on duration estimates. However, the paradigm × duration interaction was significant ($p = .03$, $\eta_p^2 = .02$). Power to detect this interaction at 80% (with four durations and two paradigms) requires at least 539 participants. Therefore, the original proposed sample for this experiment was $N = 600$. Although the thesis committee members approved this proposed sample size in October of 2021, one member suggested aiming to collect an even higher-powered sample if time and funding would allow. With that suggestion in mind, we hired four research assistants at uOttawa to assist with data collection. In total, 841 participants with normal or corrected-to-normal vision participated in this experiment between October 2019 and March 2025. With the above parameters, the sample size resulted in statistical power above 90%.

At both sites, recruitment took place via research participation systems consisting of students enrolled in psychology courses (Carleton's SONA system; University of Ottawa's ISPR system). Participants received 1.5% toward participation credits (replicating Walker et al., 2022). This study was approved by Carleton University's Research Ethics Board (Clearance # 109258) and the University of Ottawa's Ethics Board (Clearance # H-10-21-7255).

Design. To avoid a time-order effect, and given that I requested retrospective estimates from half the participants, this experiment used a between-participants design. Therefore, participants in this experiment were assigned to one of 16 conditions according to a 2 (timing: prospective vs. retrospective) × 2 (task difficulty: easy vs. difficult) × 4 (duration: 30 s, 1 minute, 2 minutes, 4 minutes) between-participants design.

The Cognitive Task. No changes were made to the task used in Walker et al. (2022) to allow results to be compared across experiments. Participants performed a visual and memory search task on a PC programmed with E-prime (Psychology Software Tools, Pittsburgh, PA). All memory set items (i.e., the targets) and non-target items (i.e., distractors) consisted of alphanumeric characters. The targets and distractors were chosen from a set of eight characters (L, R, S, H, 1, 3, 6, 7). These characters were always arranged in two lines of two digits, centred on the screen. The characters were in Times New Roman, white, 18-point font, on a black background.

The difficulty of the task was manipulated via the arrangement of targets and distractors across trials. In the easy, consistent mapping condition, four characters served as targets for the participants to search for among distractors on each trial. In this condition, the targets were always either letters or numbers, but never a mix of both categories. Therefore, each participant searched for the same targets, fixed throughout the experiment, and aimed to find their target among characters of the other category. In half the trials, one of the targets appeared among the distractors, and the participant provided a “target-present response”. In the other half of trials, none of their targets appeared in the search array; thus, they were to give a “target-absent” response. When targets are consistently mapped to a response like this, the visual search process quickly becomes automatic (Schneider & Shiffrin, 1977). The participant can then offload their

attention and working memory resources while still achieving high performance on the task and thus track time more easily in this condition.

The more difficult, varied mapping condition removed the advantages of learning through this repeated stimulus-response mapping. The targets were instead randomized on each trial, so they did not remain consistent throughout the task. Moreover, random assignment on each trial meant that targets are never guaranteed to be all digits or all letters. Rather, targets on each trail could be a mix of both categories. Therefore, any target on one trial could serve as a distractor on the next, requiring participants to ignore interfering information from the previous trial, which in turn necessitated a more controlled search process.

Procedure. The recruitment text for the ISPR system is available in Appendix A. The title for this experiment was "Visual Processing and Memory Experiment," to avoid indicating that the experiment would investigate time perception. The recruitment text outlined that the experiment could last up to 90 minutes. I chose this anchor to replicate the procedure used in Walker et al. (2022) exactly.

When a participant arrived, the experimenter asked the participant to complete the experiment alone in a quiet room. The testing rooms used for this experiment had no clocks or other time indicators. The experimenter then asked them to turn off any distracting devices, such as their phones or music devices. Participants were asked to place these items in a container in the testing room or store them in their backpacks so they were "out of sight and out of mind." As a "standard of practice," participants were asked to remove any wrist jewellery, including watches, and to set it out of sight. The experimenter told the participants that this was to prevent discomfort during the task and to ensure that the jewellery did not interfere with the quick motor responses required for high performance. However, their belongings remained in the testing

room to avoid preoccupying the participant with their whereabouts. The container or backpack containing their items was unreachable from the computer desk where the participant performed the visual and memory search task.

In the prospective condition, participants were made aware of the true purpose of the experiment. The consent form first provided this information, and they received it verbally as well. In the retrospective condition, the consent form and verbal instructions purposely excluded information about a time estimation (see Appendix B and C).

Before beginning the visual and memory search task, each participant received a detailed verbal explanation regarding the task procedure. The experimenter told participants in the prospective timing conditions that visual and memory search task performance is equally important as timing performance. Thus, all participants were asked to aim for high accuracy on the task, aiming for 90% or more in their searches.

Participants then had 20 practice trials to familiarize themselves with the task. Because both the consistent and varied mapping conditions would be more difficult in a completely novel task, these practice trials were also essential for controlling for task difficulty as much as possible. Participants were encouraged to ask questions before beginning the main task if they experienced any confusion during the practice phase. The main task began when the participant pressed the “Enter” key on a screen displaying the word “START” in large capital letters spanning the entire screen. A typical target-present trial is presented in Appendix D and proceeded as follows:

The participant first saw a fixation star in the center of the screen for 500 ms. The memory set (targets) was then presented on screen for 1000 ms for the participant to memorize. The targets were then replaced with the fixation star for 500 ms followed by the search array

containing four characters for up to 3,000 ms. On target-present trials, one of the characters presented in the memory set appeared in the search array. On target-absent trials, none of the targets appeared. Participants used their left and right hands to press the "Z" or "M" keys, respectively. Half the participants pressed "M" to indicate that the target was present, and half pressed "M" to indicate that the target was absent, thus counterbalancing the response keys across participants.

Once a response was made (or the 3,000-ms maximum was reached), the program provided feedback ("CORRECT" or "INCORRECT") to the participant and displayed it on the screen for 900 ms. This feedback also included an update on their overall accuracy on the task (e.g., "92% accurate"), so participants could track their performance and aim for their 90% accuracy goal. If the participant did not respond to a trial, the word "INCORRECT" appeared on the screen, and the software recorded a null response. After this feedback screen, there was an inter-stimulus interval (ISI) in which the participant saw a blank screen. The ISI lasted at least 100 ms, plus the remaining time from the search array. This ISI adjustment created a uniform experience on each trial. Therefore, regardless of how fast or slow a participant responded, each trial was guaranteed to be 6,000 ms long. Consequently, there were 40 trials in the four-minute task, 20 in the two-minute task, 10 in the one-minute task, and 5 in the 30-second task. To account for the uneven number of trials in the 30-second condition, the software counterbalanced the fifth trial so that half the participants received an uneven number of target-present trials. In contrast, the other half received an uneven number of target-absent trials.

Once the participant completed the visual and memory search task, a Qualtrics (Provo, UT) survey was programmed with Python to open immediately on the screen. The participants then completed the survey by providing a duration estimate indicating how long (in minutes and

seconds) they thought the task took to complete. They also provided a maximum estimate, a minimum estimate, a PoTJ, and indicated their levels of boredom and engagement, along with providing their demographic information (age and gender). Appendix E outlines these questions.

The experimenter then asked the participants if they had checked the time at any point during the experiment. Participants who performed the task in the retrospective paradigm were asked if they knew that they were taking part in a time perception experiment at any point before or during the visual and memory search task. If the participant answered yes to either of these questions, their data were excluded from the final analyses. The experimenter provided participants in the retrospective conditions with a secondary consent form detailing the true experimental purpose (Appendix F). All participants were provided with a debriefing form with more information on the experiment and contact information (Appendix G).

Experiment 1 Results

Initial Data Cleaning and Final Demographics. Of the 841 participants who completed the experiment, 72 were excluded from analysis. Fifteen participants were excluded because the experimenter accidentally provided them with the wrong consent form (e.g., they were provided with a prospective consent form, but the condition was run using retrospective instructions), and 24 participants' anonymized identity code was mistyped on either the Qualtrics questionnaire or the E-prime file (and therefore their responses could not be matched with their task performance). Sixteen participants were excluded because they chose to withdraw from the experiment. Of these 16 participants, three changed their minds about participating after they began the task. All three quoted the possibility of it lasting 90 minutes as their reason for withdrawal. Seven participants failed to learn the visual and memory search task after multiple practice sessions and decided to withdraw from the experiment. One participant left the

experiment halfway through to use the washroom, and five participants chose not to answer the time perception questionnaire at the end of the experiment. Additionally, eight participants were excluded due to a computer error (e.g., the Carleton computer crashed mid-experiment 6 times, and the Qualtrics survey failed to open 2 times at uOttawa). Finally, five participants disclosed that they knew it was a time perception experiment before participating, and four admitted to checking the time before answering the Qualtrics questionnaire. All nine participants were excluded from the analysis.

I examined the remaining 769 participants' performance on the visual and memory search task for outliers. Like Walker et al. (2022), participants were removed from the analysis if their accuracy on the visual and memory search task was 3 standard deviations (SDs) below their group's mean, or if they performed the task at chance. Such low performance was interpreted as a lack of engagement with the task or as guessing and was thus considered a failure to participate in the experiment. Thirty-five participants had outlying performance and were thus removed from the analysis, resulting in a final sample of 734 participants (ranging from 43 to 50 per group). Of the final sample, 292 participants were recruited from Carleton University (39.8%) and 442 from the University of Ottawa (60.2%). Five hundred twenty-three were female (71.3%), 204 were male, three were transgender male, and four were nonbinary. Their ages ranged from 16 to 50 years old (M = 19).

Manipulation Check. As a first step, I removed the 20 practice trials from the analysis. To test whether the difficulty of the task was successfully manipulated, a 2 (timing: prospective vs. retrospective) × 2 (task difficulty: easy vs. difficult) × 4 (duration: 30 sec, 1 min, 2 min, 4 min) ANOVA was performed on participants' visual and memory search accuracy and RTs.

Visual and Memory Search Accuracy. Levine's test was significant, $F(15, 718) = 10.2$, $p < .001$, suggesting that the group variances were not equal. This finding was expected as there should be less performance variability in an easy task (i.e., consistent mapping) than in a difficult one (i.e., varied mapping). The easy condition showed very little overall performance variance in the group (SD = .07). In contrast, the difficult condition showed greater overall group variance (SD = .12). This small difference in variance is significant given the very large sample. [4]

The average accuracy of the visual search task is depicted in Figure 8. There were no interactions between the timing paradigm, task difficulty, and duration (*p*s > .06). However, task difficulty clearly affected participants' accuracy. A significant main effect was found for task difficulty $F(1, 718) = 271.22$, $p = .001$, $\eta_p^2 = .27$. Participants were more accurate overall in the easier (consistent mapping) task ($M = 95.2\%$, $SD = .07\%$, *95%* confidence interval of the mean [94.2% 96.2%]) compared to varied mapping ($M = 83.0\%$, $SD = .12\%$, [82.0%, 84.0%]). Therefore, accuracy was significantly higher in the easy task than in the difficult task, regardless of the timing paradigm or the amount of time spent on the task. Hereafter, the square brackets will denote the 95% confidence interval of the mean.

[4] ANOVA is robust to violations of homogeneity of variance if "the ratio of largest to smallest variance is no greater than approximately 10:1" (Tabachnik & Fidell, 2007), especially when the groups have comparable sizes. None of the ANOVA's presented in this thesis exceeded this limit. Therefore, all ANOVA results described throughout this document can still be interpreted despite significant homogeneity tests. Additionally, according to Field (2024), although corrections can be implemented based on Welch procedure, "this is quite technical… and if you have anything more complicated than a 2x2 design, then, really, it would be less painful to cover your body in paper cuts and bathe in chilli sauce." With this in mind, and to ensure that the results of this experiment can be compared to previous results in the literature that do not transform their data, no transformations were performed.

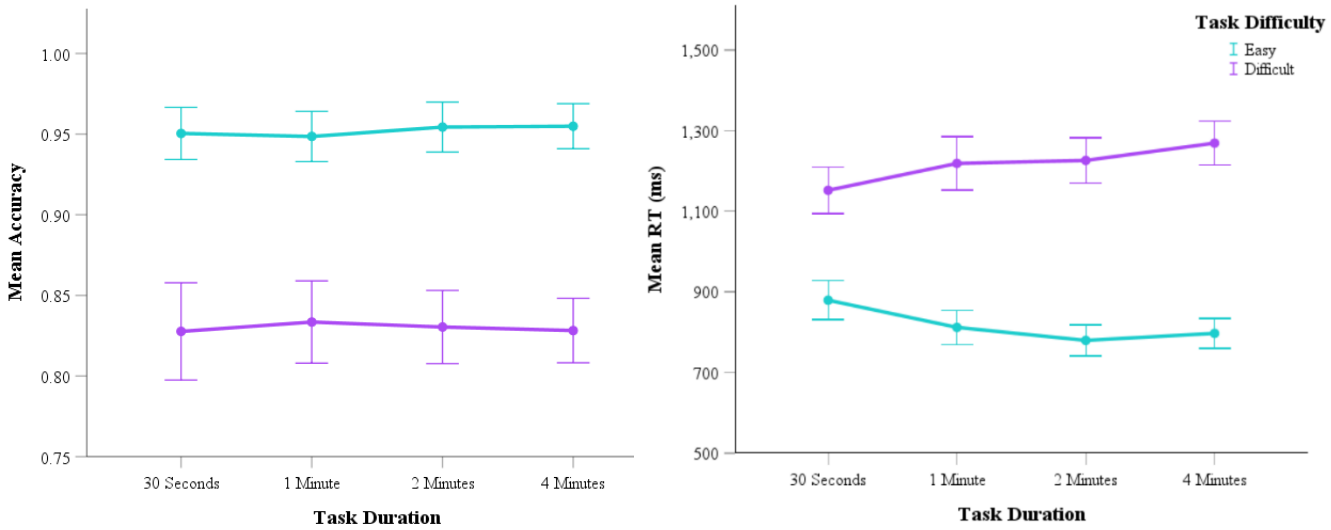


Figure 8. Left panel: Mean percentage of correct responses on the visual and memory search task. Error bars show the 95% confidence intervals of the mean. Right panel: Mean response time (RT) in milliseconds (ms) on the visual and memory search task. Error bars show the 95% confidence intervals of the mean.

Visual and Memory Search RTs. Figure 8 also shows the participants' response speed on the visual and memory search tasks. Only the RTs of accurate trials were examined. Levine's test was significant, $F(15, 718) = 5.12$, $p < .001$, again suggesting that the group variances were not equal, as would be expected of this type of task. No three-way interaction was found between the timing paradigm, task difficulty, and duration, $p > .78$. However, a two-way interaction was found between task difficulty and task duration, $F(3, 718) = 5.90$, $p = .001$, $\eta_p^2 = .02$. In the easy task, the participants were faster in their responses over time, $F(3, 718) = 2.9$, $p = .03$, $\eta_p^2 = .01$. However, in the difficult condition, participants were slower with more time spent on the task, presumably to preserve their accuracy level while fatigue accumulated, $F(3, 718) = 3.4$, $p = .02$, $\eta_p^2 = .01$. The main effect of difficulty level also shows that participants in the easy task were significantly faster ($M = 816.9$, $SD = 205.3$ [791.3, 842.6]) at responding compared to those in the difficult task ($M = 1216.4$, $SD = 287.6$, [1191.0, 1241.9]), $F(1, 718) = 472.29$, $p < .001$,

η_p^2 = .40. Based on the visual and memory search accuracy and RT results, I concluded that task difficulty was successfully manipulated in this experiment.

Time Estimation Results. In line with previous research, duration estimates were examined for outliers. Estimates that fell three standard deviations below or above the mean of their group were removed from the analysis (Tobin & Grondin, 2009; Walker et al., 2022). This resulted in the removal of five estimates. After providing their estimate, the questionnaire then asked participants to provide a maximum and a minimum time estimate. Because these estimates were used to examine participants' uncertainty, they too were screened for outlying and nonsensical responses. Specifically, anyone's responses that 1) exceeded three SDs above or below the mean of their group, and 2) contained a maximum estimate that was smaller than the minimum estimate, were removed from the following analyses. This removal resulted in the exclusion of 22 participants from the calculation of internal uncertainty. The mean duration estimates are presented in Table 3 for each of our sixteen groups (with outliers removed).

Table 3.
Group mean duration estimates (as well as group mean, minimum, and maximum estimates) in minutes.

Group	Prospective								Retrospective							
	Easy				Difficult				Easy				Difficult			
	.5	1	2	4	.5	1	2	4	.5	1	2	4	.5	1	2	4
Mean	1.5	2.4	4.1	8.1	1.6	2.7	4.9	7.9	1.9	2.2	3.3	4.7	2.0	2.8	4.1	4.5
Minimum	1.8	1.4	2.6	4.8	1.2	1.5	3.1	5.8	1.1	1.4	2.2	3.3	1.2	1.7	2.4	3.0
Maximum	2.6	3.1	6.0	9.8	2.3	3.2	6.5	10.1	2.5	3.2	4.5	6.9	2.6	3.8	6.0	6.4

Note. Mean minimum and maximum estimates represent the internal uncertainty around the group's mean.

Duration estimates were transformed into the two dependent variables (in line with Tobin et al., 2010, and Walker et al., 2022): (i) An estimate ratio was calculated by dividing each participant's time estimate by the actual task duration as per Eq. (1) on page 15 of this document. The estimate is perfectly accurate if the value is one. If the participants overestimate the task, this

value is greater than one. If the participants underestimate the task, this value is less than one. (ii) An internal uncertainty (IU) index was calculated by taking the maximum and minimum duration estimate provided by each participant, finding the difference, and dividing this difference by the actual task duration, as was presented in Eq. (2) on page 17 of this document. Higher values indicate more uncertainty.

Duration Estimates. Participants' ratios were subject to a 2 × 2 × 4 ANOVA to test average group differences and interactions among estimation paradigm, task duration, and task difficulty. Levine's test for homogeneity of variance between groups was significant, $F(15, 713) = 11.21$, $p < .001$. As in Walker et al. (2022), task duration accounted for this significant result. Variations in responses were significantly smaller in the four-minute task compared to the 30-second task. Differences in variance were thus due to the discrepancy in task durations used in this experiment.

No three-way interaction was found between timing paradigm, task difficulty, and duration. However, as illustrated in Figure 9, a significant two-way interaction was found between estimation paradigm and task duration, $F(3, 713) = 5.79$, $p = .001$, $\eta_p^2 = .02$. Following examination of the simple main effects, ratios were significantly different across estimation paradigms only in the 30 second condition, $F(1, 713) = 8.38$, $p = .004$, $\eta_p^2 = .01$, and in the four-minute condition, $F(1, 713) = 7.51$, $p < .006$, $\eta_p^2 = .01$. There was thus a cross-over interaction found between timing paradigm and task duration. Participants overestimated the 30-second task's duration more if they were part of the retrospective condition ($M = 3.99$, $SD = 3.64$ [3.56, 4.41]) as opposed to the prospective one ($M = 3.12$, $SD = .2.66$ [2.71, 3.53]). The opposite was true for the four-minute task. At four minutes, participants in the prospective group ($M = 1.99$, $SD = 1.25$ [1.57, 2.43]) overestimated the task to a greater degree than in the retrospective one

(M = 1.16, SD = .85 [.73, 1.58]). In addition to the interaction, a main effect of task duration was also found, $F(3, 713) = 31.11$, $p < .001$, $\eta_p^2 = .12$. Participants overestimated the task's duration more at 30-seconds (M = 3.56, SD = 3.18, [3.26, 3.85]) but were more accurate in their estimates (their ratios became closer to 1) at four minutes (M = 1.58, SD = 1.15 [1.28, 1.88]).

Internal Uncertainty. I next analyzed uncertainty in the participants' duration estimates. Participants' IUs were subject to a 2 × 2 × 4 ANOVA to test average group differences and interactions among estimation paradigm, task duration, and task difficulty. Considering IU is a measure of variability, it was no surprise to find the assumption of homogeneity of variance violated, $F(15, 696) = 12.11$, $p < .001$. There were no interactions found between estimation paradigm, task difficulty and task duration, $ps > .10$. However, there was a significant main effect of task duration, as shown in Figure 9, $F(3, 696) = 37.87$, $p < .001$, $\eta_p^2 = .14$.

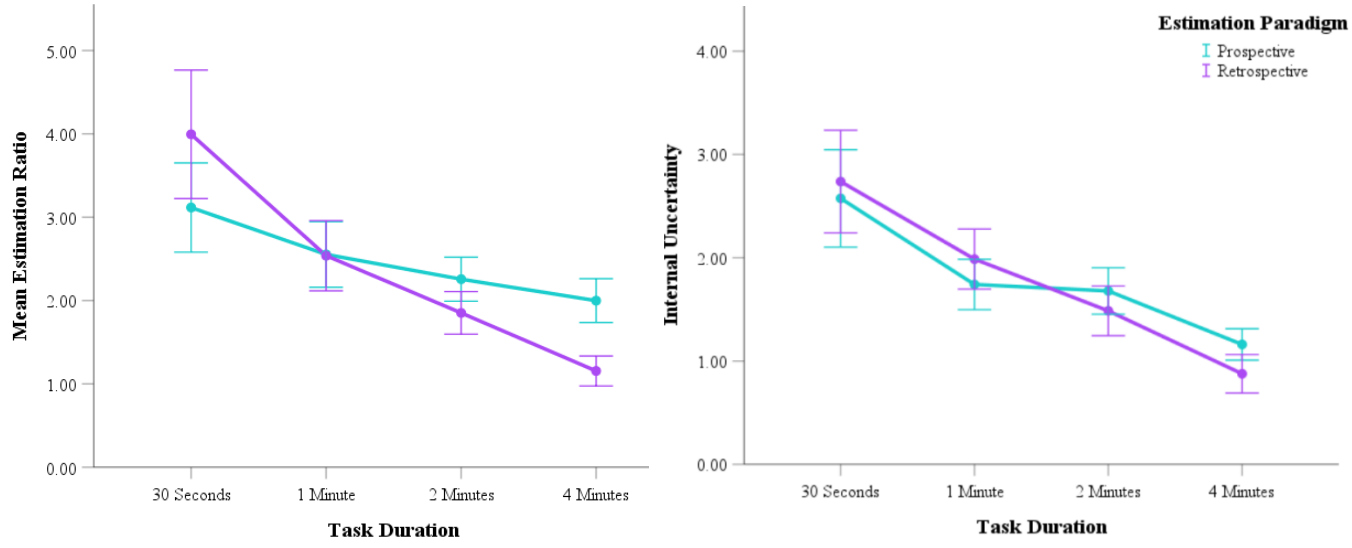


Figure 9. Left panel: Mean time estimation ratios (participants' duration estimate over the actual task duration). Both difficulty conditions are combined. Error bars show the 95% confidence intervals of the mean. Right panel: Internal Uncertainty of time estimates (the difference between the participants' maximum and minimum time estimates over the actual task duration). Both difficulty conditions are combined. Error bars show the 95% confidence intervals of the mean.

A post-hoc test was done to analyze the main effect of task duration using Tukey's HSD multiple comparison procedure to avoid Type-1 error inflation. As illustrated in Figure 9, mean IUs across all durations were significantly different from one another (all *p*s < .05), except between one and two minutes, $p = .27$. No other effects were found.

A main effect of task duration on IU was also previously observed in Walker et al. (2022). In their experiment, the average IU of the eight-minute condition ($M = .69$, $SD = .52$ [.63, .80]) was larger than the 58-minute condition ($M = .26$, $SD = .23$ [.20,.33]). In the present experiment, the average IU of the 30-second condition ($M = 2.67$, $SD = 2.29$ [2.45, 2.88]) was larger than the 4-minute condition ($M = 1.02$, $SD = .81$ [.80, 1.24]). Therefore, when investigating duration estimates across multiple intervals in an experiment, the evidence suggests that the shortest task conditions exhibit the greatest temporal uncertainty and that this uncertainty decreases progressively over task duration, at least up to 58 minutes. [5]

Subjective Experience. To explore whether participants' duration estimates were related to the feeling of passing time, participants' ratio results were correlated with their PoTJs. There was no significant relationship between these two variables when all task durations were included in the correlation ($r = -.03$, $p = .49$), demonstrating once again that duration estimates and PoTJs are distinct. However, at four minutes, participants' duration estimates correlated with PoTJs ($r = -.20$, $p < .01$). Within this four-minute condition, participants who overestimated the task the most also reported time passing the slowest. Moreover, the ratio results correlated neither with engagement ratings ($r = -.02$, $p = .56$) nor with boredom ($r = -.05$, $p = .20$).

[5] All analyses of variance (ANOVAs) were re-conducted with institutional affiliation (Carleton University and University of Ottawa) included as a covariate to assess its potential influence of experimental environment on the results. The inclusion of this covariate did not alter the pattern or significance of findings. Therefore, only analyses excluding the covariate are reported.

However, Table 4 illustrates the complex relationship between duration estimates and PoTJs as the task duration increases.

I had predicted that there would be a positive correlation between engagement and PoTJs and a negative one between boredom and PoTJs, but only in conditions lasting longer than one minute. This duration is presumably when people become spontaneously aware of the passage of time (Droit-Volet et al., 2018) and begin to appraise the activity. Therefore, I correlated PoTJ, engagement, and boredom across the four experimental task durations (See Table 4). Overall, PoTJs did correlate with both engagement ($r = .37$, $p < .001$) and boredom ($r = -.52$, $p < .001$) in the expected directions. The more engaged participants reported being, the faster time passed, and vice versa. The opposite was true for boredom. When participants rated the task as more boring, time was reported as passing more slowly. Contrary to my prediction, both engagement and boredom correlated with PoTJs across *all* durations.

Although I did not expect to find significant correlations between engagement, boredom, and PoTJs when the task was less than one minute, it is important to note that the correlation found at 30 seconds between PoTJs and engagement ($r = .27$, $p < .001$), and PoTJs and boredom ($r = -.17$, $p = .01$) is noticeably smaller than that found at four minutes between PoTJs and engagement ($r = .46$, $p < .001$), and PoTJs and boredom ($r = -.39$, $p < .001$). In other words, as the task duration increased, so too did the strengths of the relationship between PoTJ and the affective ratings of the task (level of engagement/boredom).

Table 4.
Correlations among PoTJs, engagement, boredom, and ratio separately for each task duration

		1	2	3	4
30 Seconds	1. PoTJ	----			
	2. Engagement	.27**	----		
	3. Boredom	-.17*	-.47**	----	
	4. Ratio	-.07	-.07	-.15*	

1 Minute	1. PoTJ	----		
	2. Engagement	.32**	----	
	3. Boredom	-.35**	-.58**	----
	4. Ratio	.06	-.04	.05
2 Minutes	1. PoTJ	----		
	2. Engagement	.34**	----	
	3. Boredom	-.38**	-.53**	----
	4. Ratio	-.10	-.03	.02
4 Minutes	1. PoTJ	----		
	2. Engagement	.46**	----	
	3. Boredom	-.39**	-.51**	----
	4. Ratio	-.20**	-1.8*	.08

Note. * $p < .05$. ** $p < .01$.

Exploratory PoTJ Analysis. As an exploratory analysis, the same ANOVAs as above were also conducted on PoTJs. This analysis is rarely done in the time perception literature because time perception measurements typically focus on the accuracy of people's estimates rather than their ratings of the subjective pace of time. I thus conducted this exploratory analysis to investigate whether the factors that influenced the ratio results described above (paradigm and task duration) might also influence PoTJ, thereby highlighting shared mechanisms. Additionally, because the results for task difficulty were surprisingly null in this experiment, I was curious whether task difficulty affected participants' time perception. Might a psychological time distortion have been missed if I had only analyzed duration estimates?

No three-way or any two-way interactions were found between timing paradigm, task difficulty, and task duration (ps > .16). However, a main effect of task duration was found, $F(3, 718) = 56.76$, $p < .001$, $\eta_p^2 = .04$. Participants reported that the task passed more slowly as its duration increased. Specifically, participants rated the 30-second condition as passing faster ($M = 5.81$, $SD = 1.21$[5.63, 6.01]) compared to the one-minute ($M = 5.71$, $SD = 1.23$, [5.51, 5.91]), two-minute ($M = 5.27$, $SD = 1.51$[5.01, 5.47]), and four minute condition ($M = 5.16$, $SD = 1.56$ [4.96, 5.36]). A main effect of the estimation paradigm was also found, although the

effect size is quite small, $F(3, 718) = 5.29$, $p = .02$, $\eta_p^2 = .007$. Participants rated time as passing faster in the retrospective condition ($M = 5.61$, $SD = 1.36$ [5.46, 5.75]) than in the prospective condition ($M = 5.38$, $SD = 1.46$ [5.23, 5.46]). Finally, although there was no effect of task difficulty when measuring participants' duration estimates, the exploratory ANOVA conducted on PoTJ did find a main effect of task difficulty, $F(3, 718) = 10.24$, $p < .001$, $\eta_p^2 = .14$. Participants in the easy task rated time as passing slower ($M = 5.33$, $SD = 1.60$ [5.18, 5.47]) compared to the difficult task ($M = 5.65$, $SD = 1.20$ [5.51, 5.79]).

Experiment 1 Discussion

The first aim of this experiment was to investigate how task difficulty affects the accuracy and uncertainty of estimates across task durations in the two estimation paradigms (prospective vs. retrospective). I expected to find an interaction between task difficulty and estimation paradigm at 30 seconds. Specifically, I expected prospective ratios to decrease (fewer temporal pulses accumulated) and retrospective ratios to increase (more contextual changes) with increased task difficulty. I thus expected to replicate the cross-over interaction found in Block et al. (2010), which was mainly comprised of short tasks. In conditions lasting longer than one minute, the task difficulty was expected not to be a significant moderator of duration estimation performance in either paradigm, because time perception would rely on additional information such as memory, introspection, affect, and perhaps compensatory response strategies.

Surprisingly, the task difficulty had no effect on estimation accuracy or uncertainty at any of the task durations examined, despite manipulation checks clearly showing that the two difficulty levels of the visual and memory search task differed significantly. Participants in the easy task performed better on the visual and memory search task, both in terms of accuracy and RTs. This performance benefit was observed immediately at the start of the task, showing a clear

difference in the information-processing demands across the two difficulty levels. Evidently, these clear differences in processing demands did not interfere with timing performance in this experiment. This null result, however, replicated the null result reported in Walker et al. (2022). In their experiment, Walker et al. used the exact same visual and memory search task and found no effect of task difficulty at eight and 58 minutes.

I had assumed that the null effect in Walker et al. (2022) may have resulted from the lengthy durations under investigation. After all, eight and 58 minutes could both be considered *quite* long and *very* long and therefore would have theoretically passed the boundary of attentional release. I had hoped to uncover where that boundary lay by investigating the impact of difficulty at shorter durations in this experiment (i.e., 30 seconds), with no luck.

An interesting finding emerged regarding duration estimation performance. When examining the ratio results from this experiment, a cross-over interaction was found. Retrospective estimates were greater than prospective ones at 30 seconds, whereas prospective estimates were greater than retrospective ones at four minutes. To understand this effect, it may be helpful to conceptualize the prospective and retrospective conditions as "dual-task" and "single-task" conditions, respectively. Recall that with the attention-allocation hypothesis that underpins the AGM, the presence of a non-temporal task should interfere with timing performance because it increases the demand on a limited pool of attention resources (Brown, 2006, 2008; Grondin, 2010). Prospective conditions might thus be defined as having higher "cognitive load" than retrospective conditions.

Although the processing demands of the visual and memory search task (task difficulty) did not influence estimates as expected, the cross-over effect between the timing paradigm and task duration did highlight temporal processing changes over time. At first, dividing attention

between the two tasks (timing and visual search) would be quite challenging, since both the environment and the tasks are novel. Perhaps over time, cognitive load decreases and prospective timing becomes more accurate (ratios approach 1). Considering the crossover between the two paradigms that occurred around one minute, this is perhaps where memory and introspection become more important for temporal processing than our limited attention resources.

Participants in both timing conditions severely overestimated the task duration to 30 seconds, with those in the retrospective group providing the most extreme overestimations. The average participant retrospectively guessed that the 30-second task was two minutes long! Across conditions, participants also became more accurate in their estimates as they spent more time on the task. Similarly, they became more certain in their responses over time. In other words, their estimates were not only more accurate at four minutes than at 30 seconds, but participants also provided narrower confidence ranges relative to the actual task duration.

As predicted, there was a positive correlation between engagement (and a negative correlation between boredom) and PoTJs in this experiment. Contrary to my expectation, correlations were found across all four durations examined in this experiment. However, these relations became stronger as duration increased. For example, the positive correlation between engagement and PoTJ at 30-seconds (.27) became stronger at four-minutes (.46). The negative correlation between boredom and PoTJ at 30-seconds (-.17) also became stronger at four-minutes (-.39). In longer task durations, boredom and engagement may have an increasing influence on the subjective pace of time.

Moreover, I found no relationship between PoTJs and duration estimate accuracy in this experiment. This finding provides further evidence for the claim that these two methods for measuring time perception are distinct, as the same factors do not necessarily influence them.

Yet, when correlations were performed within each duration group, a positive correlation was observed between duration estimate accuracy and PoTJ at four minutes (within this four-minute condition, participants who overestimated the task the most also reported time passing the slowest). Furthermore, boredom ratings correlated with duration estimates at 30 seconds and with engagement at four minutes. However, examining each duration condition separately inevitably compromises statistical power. Experiment 3 of this thesis will test whether boredom and engagement are related to duration estimation at four minutes when there is higher statistical power.

Intriguingly, the exploratory analysis found that task difficulty significantly impacted PoTJs. This finding directly contrasts the ratio results. Whereas difficulty had no effect on the accuracy or the uncertainty of people's duration estimates, difficulty did affect PoTJs. Participants rated the difficult task as passing more quickly than the easy one. This finding aligns with a recent study, which found that participants reported time passing more quickly during a more difficult digit-sequence task (reverse sequencing) than during an easy one (forward sequencing; Martinelli & Droit-Volet, 2022b). Therefore, the psychological time distortion produced by manipulating the difficulty of the visual and memory search task in this experiment was completely missed when measuring the participants' duration estimates. It was only by asking participants for their PoTJs that we could then observe an influence of task difficulty on people's experience of time.

Experiment 2: Exploring the Experience of Time

In both Walker (2019) and Experiment 1 of this thesis, it was found that participants' appraisals of the task (e.g., boredom and engagement) correlated with their experience of time, but only when examining PoTJ results. Moving beyond measures of engagement and boredom,

this next experiment aimed to enrich our understanding of how the features of a task might influence PoTJs and what factors are weighed when providing a duration estimate. This experiment thus investigated several features of the task experience on PoTJ. Unlike much of the research in this area, we did not use an experience-sampling method. Instead, all participants performed the same visual and memory search activity to maximize control over the secondary task. I once again manipulated the task's difficulty levels and its duration. However, rather than including brief durations such as 30 seconds or one minute, I implemented four longer durations (four, eight, 16, and 32 minutes). The durations chosen were based on Droit-Volet et al.'s (2018) experience-sampling experiment. I expected PoTJs to play a crucial role in the decision process underlying duration estimation when the task spans several minutes.

The first goal of Experiment 2 was to explore the potential effect of numerous variables on PoTJs and duration estimates, while also testing whether PoTJs are associated with duration estimates in longer tasks (like in Droit-Volet et al., 2018). In other words, what additional task qualities might influence people's sense of time? The second goal was to follow up on the null effect of task difficulty found in Experiment 1 and in Walker et al. (2022). In both experiments, the difficulty of the task had no effect on people's estimate accuracy, despite very clear differences in the information-processing demands at each difficulty level. I aimed to confirm that task difficulty does not affect duration estimates in a visual and memory search task.

Experiment 2 Research Questions and Hypotheses

Q3: Are PoTJs correlated with duration estimate accuracy or uncertainty at long durations?

H3: I hypothesized that the length of the task would impact the relation between PoTJs and duration estimates. Specifically, overestimation would occur in the shorter conditions,

replicating both Droit-Volet et al. (2018) and Walker et al. (2022). However, I predicted that participants would report that time passed more quickly in the short conditions (four and eight minutes) and more slowly in the longer conditions (16 and 32 minutes). I thus expected to find a correlation between PoTJs and duration estimates. Therefore, conditions with the most overestimation would also rate time as passing more quickly and vice versa.

Q4: Are there key factors influencing the relation between PoTJs and duration estimation that have been previously overlooked?

H4: I predicted that participants' perception of time would be influenced by their internal appraisal of several task qualities (e.g., subjective level of difficulty, fun, novelty, etc., discussed in the next section).

Q5: Does the difficulty of the task impact duration estimates?

H5: I predicted that the difficulty (i.e., the information processing demands) of the task would have no impact on estimation accuracy, which would replicate the null effect of task difficulty found in Experiment 1 and in Walker et al. (2022).

Q6: Do certain task qualities impact the *certainty* of people's estimates?

H6: Although the difficulty of the task may not impact their estimation accuracy, I predicted that several of the tasks' qualities would make people less confident in their estimates. However, this was an exploratory hypothesis, and thus no specific task qualities nor any directionality were pre-registered.

Experiment 2 Method

The following experiment was preregistered on the Open Science Framework (OSF) at https://osf.io/hg6b3/.

Participants. Three hundred forty-five participants with normal or corrected-to-normal vision participated in this online experiment between January and June of 2022. Recruitment took place through the University of Ottawa's research participation system (ISPR). Participants completed the experiment via ISPR and received 1.5% toward research participation credits because they were told the experiment could last up to 90 minutes but might end at any point before this maximum was reached (replicating the instructions of Experiment 1). The University of Ottawa Research Ethics Board approved this experiment (# H-01-22-7728).

Design. This experiment was conducted online and focused only on the prospective paradigm in which participants were aware that they would estimate the task's duration. Participants were randomly assigned to a four-minute, eight-minute, 16-minute, or 32-minute task (replicating four of the durations from Droit-Volet et al., 2018). In each condition, participants performed either the easy or the difficult version of the visual and memory search task, resulting in a 4 × 2 design. As in Experiment 1, a between-participants design was used to avoid time-order effects in which the participant's first estimate biases subsequent estimates.

Cognitive Task. I used the same visual and memory search task as in Experiment 1 for Experiment 2. The task and the subsequent questionnaire were programmed in Qualtrics so that participants could complete the experiment on their personal computers.

Procedure. The ISPR recruitment text for this experiment explained that the experiment could last up to 90 minutes, and thus, they received 1.5 credits for participation. Although the task conditions lasted a maximum of 32 minutes, all participants received the full 1.5 credits upon completion of the experiment because they set aside 90 minutes of their day. The recruitment text clearly indicated that the experiment must be performed on a desktop computer or laptop. The experimenter told them not to use their phones or devices during this experiment.

After informed consent was obtained, participants watched a video of the experimenter asking them to complete the experiment alone in a quiet room. They were asked to remove any clocks, watches, smartphones, or other time indicators. To hide the time on the participant's computer screen, the researcher asked the participant to tape a small piece of paper to the corner of the screen where the time appeared. The experimenter then verbally provided the task instructions through video. The participant saw a brief on-screen demonstration of the visual and memory search task. They then received 20 practice trials to familiarize themselves with the task.

Once the task was completed (which included 20 practice trials, followed by 40 trials in the four-minute task, 80 in the eight-minute task, 160 in the 16-minute task, and 320 in the 32-minute task), a survey was presented on screen. Participants were asked to complete the survey questions outlined in Appendix H. These questions were inspired by Larson (2006) and Droit-Volet et al. (2017). The questions covered a range of experiences related to both the participants' appraisal of the task and their time perception. Given the length of this questionnaire, I included an item to assess response validity. Therefore, "I have never used a computer" (Huang, Liu, and Bowling, 2015) was embedded to detect insufficient effort in responding.

Appendix H also contains the check-in questions posed to participants after the task was completed. They were also asked in an open-ended question whether any psychological factors may have influenced the results. The questionnaire asked participants whether they checked the time at any point during the experiment, as well as questions related to their environment and the experimental setup. Per the suggestion of a committee member, I also included a screening question on alcohol use. All participants were provided with a detailed debriefing form and encouraged to forward their questions to the experimenter. The experiment flow, questionnaire, consent forms, and debriefing form are outlined in Appendix H.

Experiment 2 Results

Initial Data Cleaning and Final Demographics. All the participants reported following the instructions to complete the experiment using a keyboard in a quiet room. No participants reported being under the influence of alcohol during the experiment. Three participants reported cannabis use, but did not indicate whether they used cannabis prior to performing the task. Two participants indicated that they take antidepressant medication, four indicated that they were experiencing significant levels of stress, one indicated chronic pain, one indicated illness (COVID-19), one indicated caffeine withdrawal, and one indicated "fear of failure" as variables possibly affecting their time perception. These thirteen participants represented 3.8% of the sample. A diagnosis of ADHD was the most endorsed psychological factor possibly affecting participant performance. However, too few individuals indicated having ADHD to compare the results across clinical and non-clinical groups (N =18, 5.2% of the sample). Considering how few participants endorsed potential psychological considerations, and since these conditions were not pre-registered exclusion criteria, these participants remained in the final sample.

Of the 345 participants who completed the experiment, 20 were excluded from the analyses because they performed the visual and memory search experiment at chance. These participants were removed from the study because they were likely inattentive to the task and were thus unaffected by the cognitive load manipulation. Twenty-three were excluded because they reported checking the time throughout the task, and seven were removed for failing the validity check question. I then examined the initial duration estimates of the remaining 295 participants for outliers. In keeping with the methods used in Experiment 1, estimates were removed if they were three SD's below or above the mean for their group (like Tobin & Grondin, 2009). Three participants provided outlying initial duration estimates and were thus removed

from the analysis, resulting in a final sample of 292 participants (ranging from 29 to 40 per group). Two hundred sixteen participants were female (74%), 66 were male, two were transgender male, two were nonbinary, one was gender fluid, and six reported their gender identity as cisgender with no further details provided. Their ages ranged from 16 to 36 years old ($M = 19$).

Manipulation Check. The 20 practice trials that the participants completed were removed from the analysis. To test whether the task's difficulty was successfully manipulated, I performed a 2 (difficulty: easy vs. difficult) × 4 (duration: 4 min, 8 min, 16 min, 32 min) ANOVA on participants' visual and memory search accuracy and RTs.

Visual and Memory Search Accuracy. Levine's test was significant, $F(7, 284) = 15.67$, $p < .001$, suggesting that the group variances were not equal. This finding was expected, however, given that there should be less variability in an easy task (i.e., consistent mapping) than in a difficult one (i.e., varied mapping), as was found in this experiment. The results of the ANOVA are shown in Figure 10. A two-way interaction between task difficulty and duration was found, $F(3, 284) = 3.70$, $p = .012$, $\eta_p^2 = .04$.

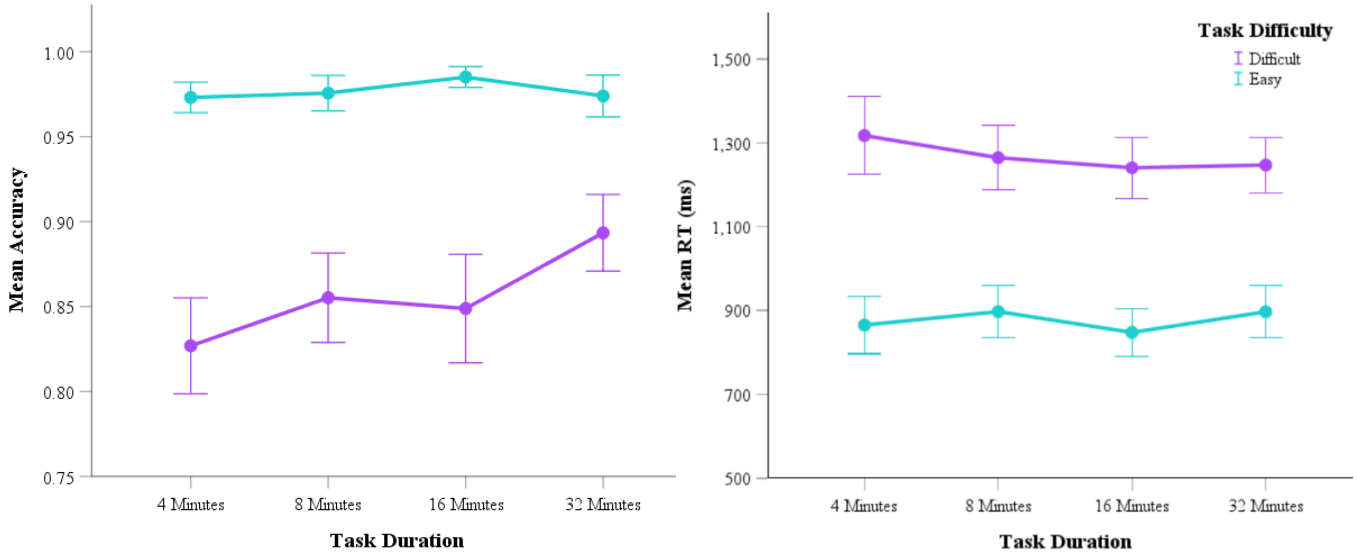


Figure *10*. Left panel: Mean percentage of correct responses on the visual and memory search task. Error bars show the 95% confidence intervals of the mean. Right panel: Mean response time (RT) in milliseconds (ms) on the visual and memory search task. Error bars show the 95% confidence intervals of the mean.

The overall difficulty of the task clearly affected participants' accuracy. Specifically, a significant main effect was found for task difficulty $F(1, 284) = 276.56$, $p = .001$, $\eta_p^2 = .49$. Participants were more accurate overall when the task was easier (featured consistent mapping) ($M = 97.7\%$, $SD = 2.9\%$ [96.7, 98.7]) compared to varied mapping ($M = 85.3\%$, $SD = 8.6\%$ [84.6, 86.6]). Therefore, accuracy was significantly higher in the easy task condition than in the difficult task condition, regardless of the time spent on the task.

The duration of the task significantly affected accuracy only in the varied mapping (difficult) condition. Specifically, mean accuracy in the more difficult (varied mapping), 32-minute condition ($M = 89.3\%$, $SD = 5.9\%$ [86.3, 92.4]) was significantly higher than mean accuracy in the varied mapping, four-minute condition ($M = 82.7\%$, $SD = 8.8\%$ [80.1, 85.3]). In other words, higher accuracy was observed when participants had more practice on the task. However, there was no significant difference in accuracy when response mapping was consistent, nor were there significant differences in response accuracy between the other task durations. Participants thus reached a high level of accuracy in the visual and memory search task very early in the experiment, and they saw little benefit from task duration (i.e., practice), except in the more difficult task condition.

Visual and Memory Search RTs. In Figure 10, only RTs on accurate trials were examined. Levine's test was significant, $F(7, 284) = 3.37$, $p = .002$, again suggesting that the group variances were not equal, as would be expected of this type of task. No two-way interaction was found, nor was there any main effect of task duration on participants' overall RTs. A main effect of difficulty was found, however, $F(1, 284) = 240.52$, $p < .001$, $\eta_p^2 = .46$.

Participants were significantly faster at responding in the easy condition (M = 876.4, SD = 189.1 [842.3, 911.5]) compared to the difficult condition (M = 1269.3, SD = 236.3 [1231.8, 1302.8]). Based on the visual and memory search accuracy and RT results, I concluded that task difficulty was successfully manipulated in this experiment.

Duration Estimation Results. The following steps were taken to analyze participants' duration estimates. I first performed the same data analysis procedures used in Experiment 1 to examine how the duration and difficulty of the task affected people's duration estimates and uncertainty at longer durations. Like Experiment 1, I transformed duration estimates into ratio and IU variables. These variables were then subjected to a 2 × 4 between-subjects ANOVA comparing accuracy and uncertainty in duration estimates across the two levels of task difficulty and the four durations (four, eight, 16, and 32 minutes).

Duration Estimates. Levine's test for homogeneity of variance between groups was significant, $F(7, 284) = 8.64$, $p < .001$. As in Walker et al. (2022), task duration accounted for this significant result. Variations in responses were significantly smaller in the 32-minute task than in the four-minute task. Differences in variance were thus due to the large discrepancy in task durations used in this experiment.

The ANOVA revealed a significant two-way interaction between task difficulty and task duration, $F(3, 284) = 4.05$, $p = .008$, $\eta_p^2 = .04$. This was unexpected, since this effect had not been found in prior experiments using the same visual and memory search task (Walker et al., 2022; Experiment 1 of this thesis). Following examination of the simple main effects, task difficulty had a significant effect on participants' estimation ratio, but only in the four-minute task, $F(1, 284) = 15.34$, $p < .001$, $\eta_p^2 = .05$. As seen in Figure 11, participants overestimated the four-minute task's duration more if they were part of the difficult task condition (M = 2.34,

SD = 1.02 [2.13, 2.55]) as opposed to the easy one (*M* = 1.75, *SD* = .78 [1.54, 1.96]). Table 5 displays the data in minutes, rather than estimation ratios.

Table 5.

Group mean duration estimates (as well as group mean minimum and maximum estimates) in minutes.

Group	4 minutes		8 minutes		16 minutes		32 minutes	
	Easy	Difficult	Easy	Difficult	Easy	difficult	Easy	Difficult
Mean Estimate	7.0	9.3	11.7	13.3	20.0	18.3	34.2	33.7
Minimum	5.1	6.3	9.1	9.5	15.9	12.2	26.6	25.5
Maximum	10.0	12.5	16.2	18.3	28.9	23.4	42.1	38.7

Note. Mean minimum and maximum estimates represent the internal uncertainty around the group's mean.

The ANOVA also revealed a significant main effect of duration, $F(3, 284) = 31.13$, $p < .001$, $\eta_p^2 = .25$. On average, participants overestimated the duration of the four-minute task (*M* = 2.04, *SD* = .95 [1.89, 2.19]) and the eight-minute task (*M* = 1.57, *SD* = .71 [1.41, 1.72]) and were fairly accurate at estimating the duration of the 16-minute (*M* = 1.20, *SD* = 47 [1.04, 1.35]) and 32-minute tasks (*M* = 1.06, *SD* = 43 [.90, 1.23]). The result of the eight-minute condition is especially interesting because it aligns with Walker et al. (2022), who found a significant overestimation in their eight-minute condition (*M* = 1.33, *SD* = .52 [1.26, 1.40]). These results also align with Tobin and Grondin (2009), who found a significant overestimation in their eight-minute condition (*M* = 1.44). However, unlike in the present experiment, participants in Tobin and Grondin's (2009) experiment underestimated the 24-minute condition (*M* = .80).

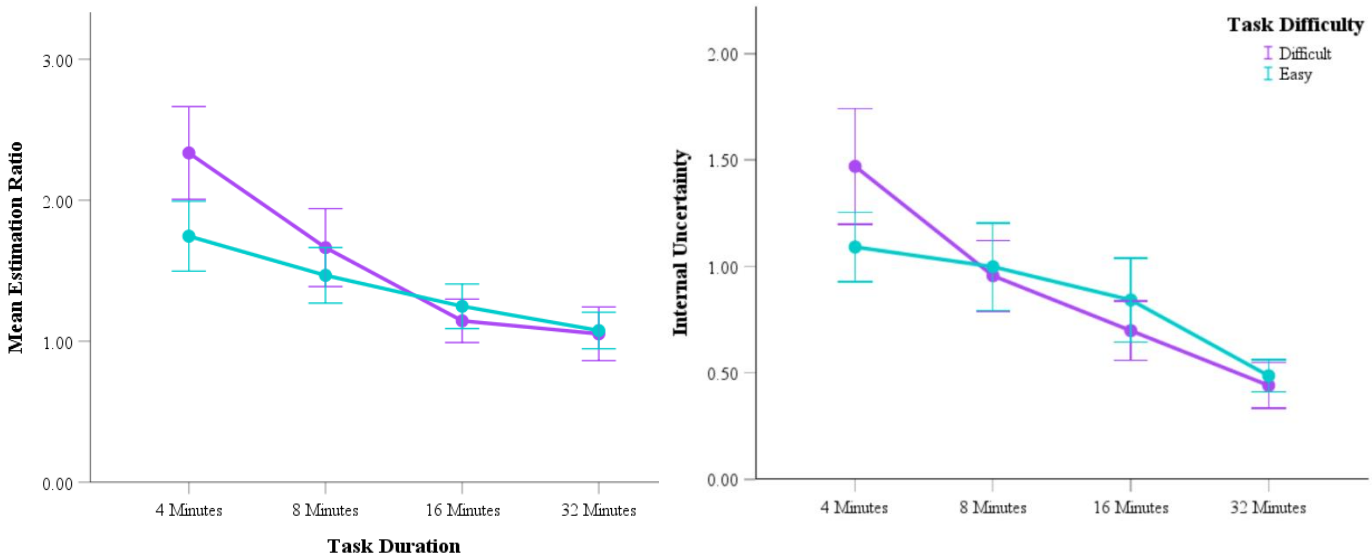


Figure 11. Left panel: Mean time estimation ratios (participants' duration estimate over the actual task duration). Error bars show the 95% confidence intervals of the mean. Right panel: Internal Uncertainty of time estimates (the difference between the participants' maximum and minimum time estimates over the actual task duration). Error bars show the 95% confidence intervals of the mean.

Finally, a main effect of task difficulty was found. Once again, this was an unexpected result. Overall, participants overestimated the duration of the task when they were in the difficult task condition (M = 1.56, SD = .91 [1.44, 1.66]) compared to the easy one (M = 1.39, SD = .63 [1.28, 1.49]), however, the size of the effect is small: $F(1, 284) = 4.34$ $p = .04$, $\eta_p^2 = .02$. Notably, the direction of this effect is opposite of what is typically observed of prospective time estimation tasks. Rather than overestimating task duration under difficult task conditions, participants typically underestimate it when a secondary task is implemented in a prospective timing paradigm (Brown, 1997). Perhaps with the long durations used in this experiment, estimates behaved more similarly to retrospective estimates, as some researchers have previously suggested (e.g., Block & Gruber, 2014).

Internal Uncertainty. The uncertainty in participants' time estimates was measured. After providing their time estimate, participants were then asked to provide a maximum and a minimum time estimate. Because these estimates were used to derive the IU, they too were

screened for outlying and nonsensical responses. Specifically, anyone's responses that 1) exceeded three SDs above or below the mean of their group, and 2) contained a maximum estimate that was smaller than the minimum estimate, were removed from the following analyses. This removal resulted in the exclusion of nine participants. Considering that IU is a measure of group variability, it was no surprise to find the assumption of homogeneity of variance was violated, $F(7, 275) = 8.19$, $p < .001$.

Like ratio, a two-way interaction was found between task difficulty and task duration, as illustrated in Figure 15, $F(3, 275) = 3.56$, $p < .02$, $\eta_p^2 = .04$. Analysis of simple main effects revealed that task difficulty had a significant effect on IU in the four-minute condition only, $F(1, 275) = 9.55$, $p = .002$, $\eta_p^2 = .03$. Specifically, participants in the four-minute condition had a higher IU if they were also in the difficult condition ($M = 1.47$, $SD = .84$ [1.29, 1.65]) as opposed to the easy one ($M = 1.09$, $SD = .49$ [.93, 1.26]). Furthermore, there was a significant main effect of duration, $F(3, 275) = 28.52$, $p < .001$, $\eta_p^2 = .24$. This effect was also observed in Experiment 1 and in Walker et al. 2022. Therefore, in line with previous results, when investigating duration estimates across multiple time spans in an experiment, the shortest task condition again shows the greatest uncertainty. This effect appears to be robust.

Direct Replication (Tandarich, 2026). Due to the unexpected effect of task difficulty on duration estimates found in Experiment 2, there was concern that the effect of task difficulty could be a Type 1 error. Considering that two other experiments examining task difficulty over long durations failed to find such an effect and that the effect's direction opposed prospective timing theories, a follow-up investigation was conducted to determine whether the effect would replicate. An honours thesis student, Ms. Erika Tandarich, therefore conducted a direct replication of Experiment 2. She re-ran the experiment, keeping the experimental design and the

visual and memory search task the same. She preregistered this experiment on the Open Science Framework (OSF), including an extension to the final research questionnaire: https://osf.io/h6935/

After data cleaning, which followed the same procedures as in Experiment 2 (as pre-registered on OSF), Tandarich (2026) analyzed the task performance and duration-estimate results from 406 participants. Recruitment once again took place through the University of Ottawa's research participation system (ISPR) and concluded in December of 2025. The participants completed the experiment via ISPR and received 1.5% toward research participation credits because they were told that the experiment could last up to 90 minutes but might end at any point before this maximum was reached (replicating the instructions of Experiments 1 and 2). The manipulation check for this replicated experiment is illustrated in Figures 12 and 13 alongside the original results of experiment 2, confirming that the difficulty of the visual and memory search task was successfully manipulated once again.

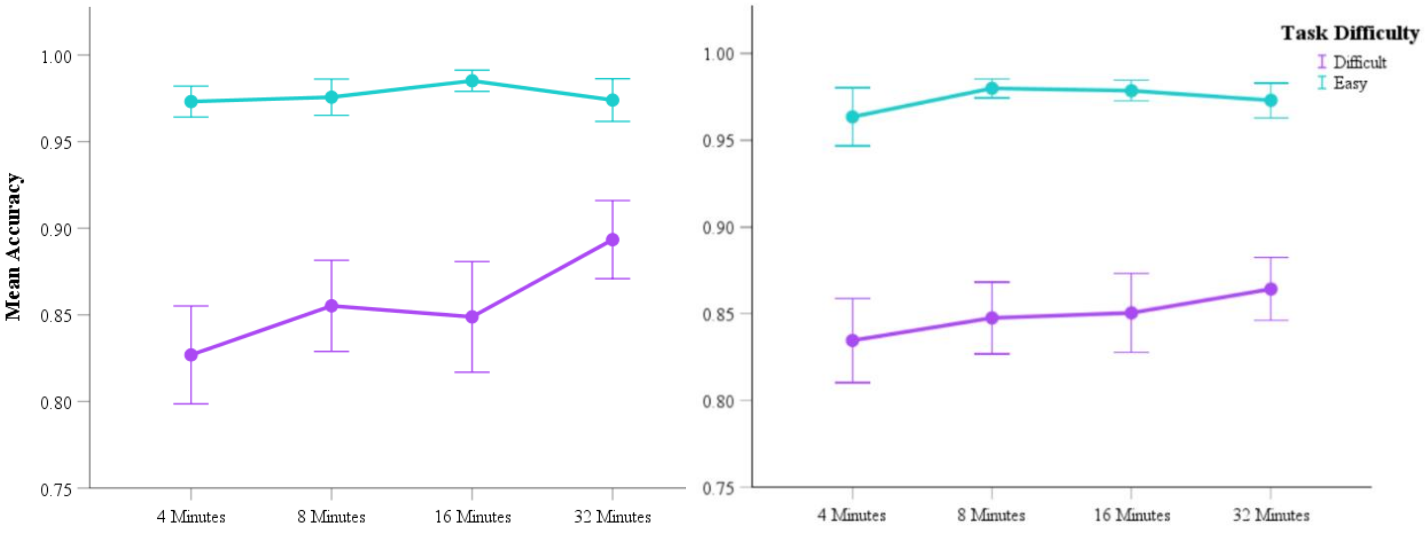


Figure 12. Mean percentage of correct responses on the visual and memory search task. The left panel shows the original results of Experiment 2. The right panel shows the replication results by Tandarich (2026). Error bars show the 95% confidence intervals of the mean.

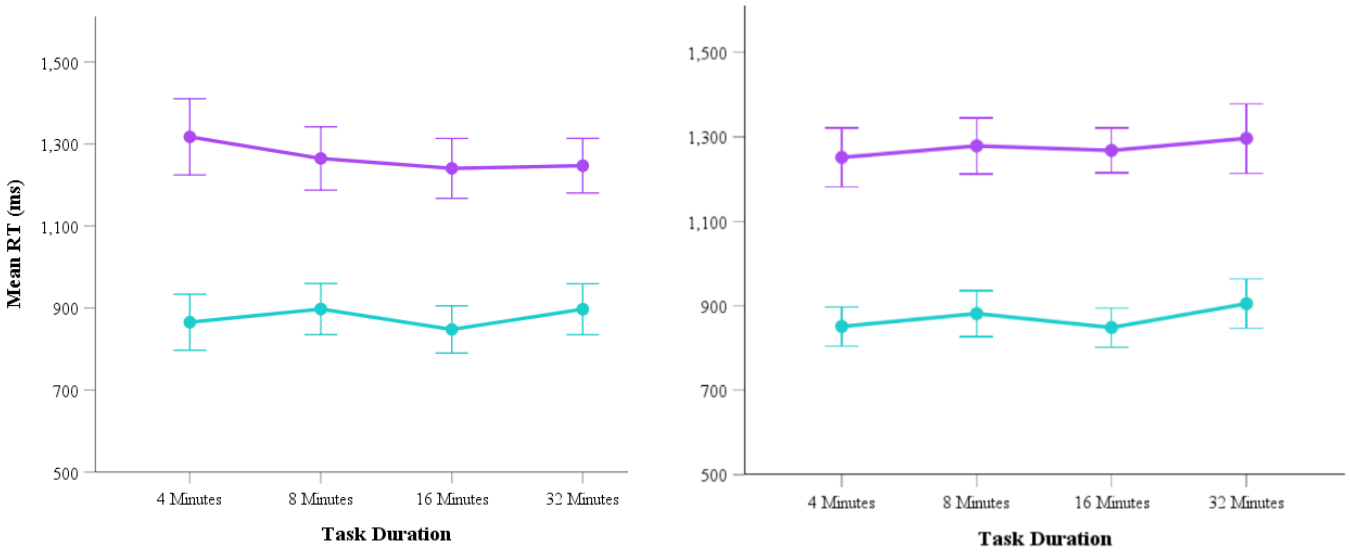


Figure 13. Mean response time (RT) in milliseconds (ms) on the visual and memory search task. The left panel shows the original results of Experiment 2. The right panel shows the replication results by Tandarich (2026). Error bars show the 95% confidence intervals of the mean.

The duration estimates, summarized in Table 6, were converted into estimation ratios and IU variables. Other than the four-minute task, the duration estimate results replicated across task conditions.

Table 6.
Group mean duration estimates in minutes in Experiment 2 and Tandarich's (2026) direct replication.

Group	4 minutes		8 minutes		16 minutes		32 minutes	
	easy	difficult	Easy	difficult	Easy	difficult	Easy	Difficult
Experiment 2	7.0	9.3	11.7	13.3	20.0	18.3	34.2	33.7
Tandarich (2026)	6.4	7.3	13.3	11.9	20.0	19.7	35.7	33.2

In line with Experiment 2, two 2 × 4 between-subjects ANOVAs were conducted on the replication data to compare estimation accuracy and uncertainty across the same two levels of difficulty (easy and difficult) and four durations (four, eight, 16, and 32 minutes). Figure 14 illustrates the ratio and IU results of the replicated experiment alongside the original results.

Tandarich (2026) successfully replicated the effect of task duration on the ratio results found in Experiment 2, $F(3, 398) = 17.245$, $p < .001$, $\eta_p^2 = .12$. Participants' duration estimates were more accurate in the longer task conditions (16 and 32 minutes) compared to the shorter tasks (four and eight minutes). The shorter conditions were overestimated once more. However, the main effect of task difficulty did not replicate, nor did the interaction between task duration and difficulty ($ps > 1.6$). Similarly, Tandarich (2026) found that task duration significantly affected IU results, $F(3, 398) = 25.99$, $p < .001$, $\eta_p^2 = .16$, with participants showing less uncertainty as task duration increased. There were no effects of task difficulty, nor was there any interaction between task difficulty and task duration in this direct replication ($ps > .29$).

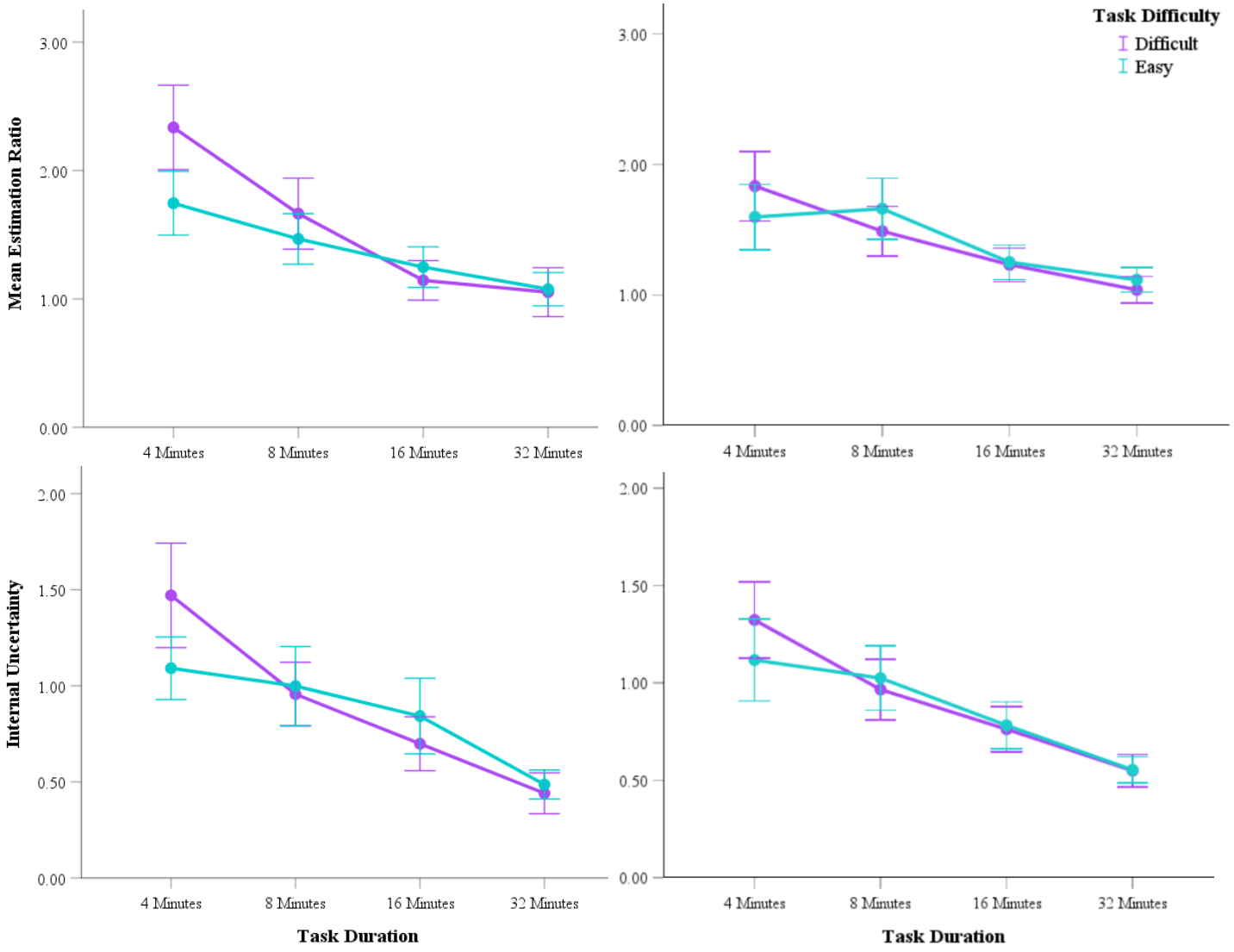


Figure 14. Top panels: Mean estimation ratios (participants' duration estimate over the actual task duration). Bottom panels: Internal Uncertainty of estimates (the difference between the participants' maximum and minimum duration estimates over the actual task duration). The left panel shows the original results of Experiment 2. The right panel shows the replication results by Tandarich (2026). Error bars show the 95% confidence intervals of the mean.

Subjective Experience. To explore whether participants' duration estimates were related to the feeling of time passing in Experiment 2, participants' ratio results were correlated with their PoTJs. Furthermore, IU results were correlated with PoTJs to examine whether participants' level of uncertainty correlated with the perceived flow of time. Then, predictors of participants' duration estimate accuracy (ratio), IU, and PoTJs were investigated. Specifically, the task's duration and difficulty were entered as predictors in a hierarchical linear regression for each of these outcome variables. The remaining questionnaire variables (including engagement, boredom, attention, subjective difficulty, expectation, novelty, fun, skill, and distraction) were entered together in a second step to investigate whether any of these factors explain variance in estimation or PoTJs beyond task difficulty and task duration.

A significant correlation was found in Experiment 2 between ratios and PoTJs ($r = .37$, $p < .001$). As expected, conditions with the most overestimation were counter-intuitively also rated as passing "faster." That is, participants overestimated the four- and eight-minute tasks ($M = 8.16$ minutes and 12.5 minutes, respectively) more than the 16- and 32-minute tasks ($M = 19.12$ minutes and 34.07 minutes, respectively). Yet, they reported time as passing more quickly on a 7-point scale in the four- and eight-minute tasks ($M = 4.83$ and 3.77), compared to the 16- and 32-minute tasks ($M = 3.00$ and 2.13). This result is like that of Walker (2019), in which participants overestimated the eight-minute task ($M = 10.7$ minutes) and underestimated the 58-minute task ($M = 42.5$ minutes). Likewise, they reported that time passed significantly faster on a Likert scale during the eight-minute task ($M = 4.1$) than during the 58-minute task in

that experiment ($M = 2.5$), $r = .27$, $p < .001$. The current experiment thus replicates the finding of Walker (2019), revealing once again that participants overestimate a task that they deem to pass quickly, rather than underestimating the time as one might expect.

Of note, when correlations were analyzed at the group-level by examining PoTJs and ratio results within the four-minute, eight-minute, 16-minute, and 32-minute groups (Figure 15), a significant relationship between PoTJs and ratio was only found in the four-minute task ($r = .26$, $p = .02$). In the other task durations, no significant relation was found between ratio and PoTJs in the present experiment. Therefore, when broken down by duration, the significant correlation between PoTJs and the ratio disappears in all groups except at four minutes (N = 80).

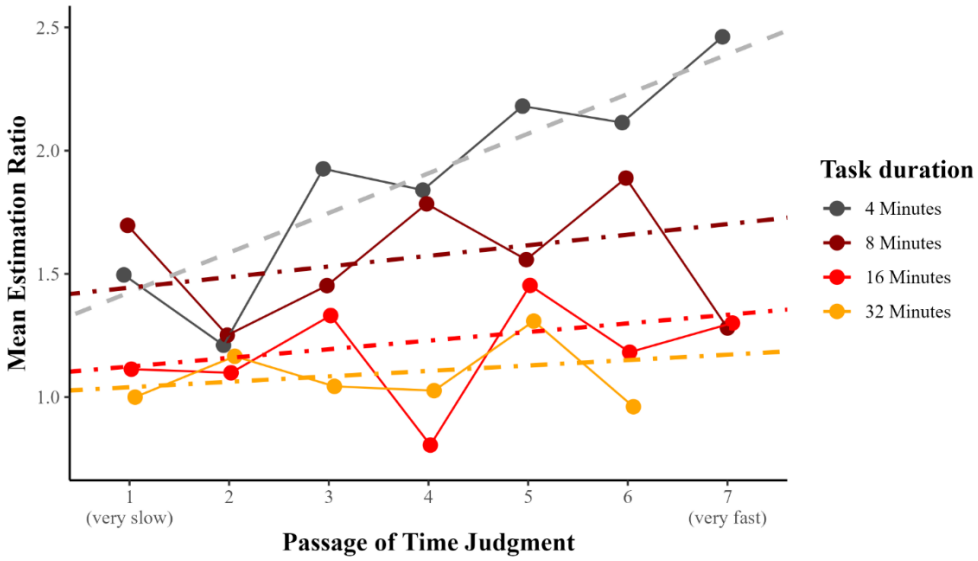


Figure 15. Relationship between mean estimation ratio and PoTJs broken down by task duration.

In Tandarich's (2026) direct replication of this experiment, however, she found no significant correlation between ratios and PoTJs ($r = .09$, $p = .09$). Moreover, when Tandarich (2026) examined correlations within each task duration condition separately (four, eight, 16, and 32 minutes), she found no significant relationships in any condition ($p > .06$). Experiment 3 will thus investigate this inconsistent relationship between PoTJs and ratio at four-minutes.

Furthermore, in Experiment 2, it was found that IU and PoTJs were correlated as well ($r = .32$, $p < .001$). That is, participants who reported time as passing more quickly also reported wider ranges of uncertainty for their duration estimates. However, as with the ratio results, there was no correlation between IU and PoTJs when task durations were examined individually. In other words, when the data is split into groups to examine correlations *within* the four-minute, eight-minute, 16-minute, and 32-minute tasks, there appears to be no relationship between participants' level of uncertainty and the subjective speed of time experienced during the experiment. Instead, it is the task duration that appears to drive the correlation found above.

The results of all the linear regressions of Experiment 2 are presented next and outlined in Table 7.

Table 7.

Linear model of predictors of the estimation ratio.

	***b* (95% CI)**	***SE***	**β**	***t***	***p***
Step 1					
Constant	2.56 (2.26, 2.87)	.15		16.58	< .001
Task Difficulty	-.18 (-.34, .02)	.08	-.12	-2.24	.026
Task Duration	-.33 (-.40, -.26)	.04	-.47	-9.03	< .001
Step 2					
Constant	2.97 (2.17, 3.76)	.41		7.33	< .001
Task Difficulty	-.10 (-.31, .10)	.11	.07	-.98	.33
Task Duration	-.32 (-.40, -.24)	.04	-.45	-7.61	< .001
Engagement	-.03 (-.09, .04)	.04	-.05	-.72	.47
Boredom	-.02 (-.07, .03)	.03	.05	-.73	.47
Attention (focus)	.01 (-.07, .09)	.04	.02	.28	.78
Subj. difficulty	.02 (-.04, .08)	.03	.05	.63	.53
Newness	-.02 (-.07, .02)	.02	-.06	-1.00	.32
Fun	.002 (-.06, .06)	.03	.01	.07	.95
Skill (capability)	-.05 (-.11, .01)	.03	-.09	-1.54	.12
Distraction	-.03 (-.08, .02)	.03	.06	-1.12	.27

Note. $R^2 = .23$ for Step 1; $\Delta R^2 = .02$ for Step 2 ($p = .51$).

Linear model of predictors of IU

	***b* (95% CI)**	***SE***	**β**	***t***	***p***
Step 1					
Constant	1.60 (1.36, 1.85)	.12		13.02	< .001
Task Difficulty	-.04 (-.17, .08)	.06	-.35	-.67	.50
Task Duration	-.27 (-.32, -.21)	.03	-.48	-9.06	< .001
Step 2					
Constant	1.29 (.65, 1.92)	.32		3.99	< .001
Task Difficulty	-.07 (-.24, -.09)	.08	-.06	-.87	.38
Task Duration	-.29 (-.35, -.22)	.03	-.51	-8.51	< .001
Engagement	-.01 (-.06, .05)	.03	-.02	-.24	.81
Boredom	.05 (.01, .10)	.02	.18	2.53	.01
Attention (focus)	.04 (-.02, .10)	.03	.09	1.27	.21
Subj. difficulty	-.02 (-.07, .03)	.03	-.06	-.74	.46
Newness	-.01 (-.04, .03)	.02	-.02	-.29	.77
Fun	.03 (-.02, .08)	.02	.08	1.15	.25
Skill (capability)	-.02 (-.07, .03)	.03	-.04	-.67	.50
Distraction	-.02 (-.02, .06)	.02	.06	1.01	.31

Note. $R^2 = .23$ for Step 1; $\Delta R^2 = .03$ for Step 2 ($p = .31$).

Linear model of predictors of PoTJ

	***b* (95% CI)**	***SE***	**β**	***t***	***p***
Step 1					
Constant	7.15 (6.50, 7.80)	.33		21.47	< .001
Task Difficulty	-1.02 (-1.36, -.67)	.18	-.28	-5.83	< .001
Task Duration	-.88 (-1.03, -.72)	.08	-.53	-11.09	< .001
Step 2					
Constant	5.17 (3.64, 6.70)	.77		6.68	< .001
Task Difficulty	-.40 (-.80, -.07)	.02	-.11	-2.0	.046
Task Duration	-.56 (-.71, -.40)	.08	-.33	-6.89	< .001
Engagement	-.08 (-.05, .22)	.07	.08	1.27	.21
Boredom	-.31 (-.41, .21)	.05	-.34	-6.12	< .001
Attention (focus)	.03 (-.11, .18)	.07	.03	.45	.66
Subj. difficulty	.11 (-.01, .23)	.06	.11	1.82	.07
Newness	-.02 (-.11, .06)	.05	-.02	-.50	.62
Fun	.07 (-.05, .18)	.06	.07	1.18	.24
Skill (capability)	-.06 (-.06, .18)	.06	.05	.94	.35
Distraction	-.09 (-.01, .18)	.05	.08	1.80	.07

Note. $R^2 = .36$ for Step 1; $\Delta R^2 = .15$ for Step 2 ($p < .001$).

From the regressions conducted above, the task duration and difficulty are significant predictors of participants' estimate accuracy (ratio). Adding additional variables to the model (engagement, boredom, attention, subjective difficulty, newness, fun, skill, and distraction) did not predict the ratio results beyond task duration and difficulty. Similarly, most of the exploratory variables did not add explanation to the IU results either. In fact, task duration and boredom were the only variables that significantly predicted uncertainty in this experiment. This finding contradicted my hypothesis. I predicted that people's certainty would be influenced by a variety of factors, with the duration estimate formulated on the basis of an internal appraisal of the task's qualities. From the results of this experiment, it appears that boredom is the only appraisal to significantly predict uncertainty in duration estimates, over and above the main independent variables.

Like the ratio results, task duration and task difficulty were both significant predictors of PoTJs. This finding replicated Experiment 1's exploratory analysis in which task difficulty and duration both significantly altered PoTJ. However, contrary to predictions, only boredom was significantly related to PoTJ results when the exploratory variables were added to the model. However, I noticed that both subjective difficulty and level of distraction were marginally significant in the model. Therefore, along with boredom, subjective task difficulty and distraction were identified as potentially important factors underlying differences in PoTJs across participants and warranting a follow-up investigation.

Experiment 2 Discussion

The first aim of this experiment was to investigate whether PoTJs correlate with estimate accuracy and uncertainty at long durations. Participants' duration estimates (which were influenced by both task length and difficulty, especially at four minutes) were indeed correlated

with PoTJs. Participants in the shorter tasks (four and eight minutes) overestimated the task duration on average, yet they reported time as passing quickly. Similarly, participants' estimation uncertainty, which was significantly affected by task duration, was correlated with PoTJs. Wider ranges of uncertainty were observed in conditions where participants reported time passing more quickly. However, these associations were only found when all conditions were included in the correlation analysis. When examining intra-group correlations between PoTJs and duration estimate accuracy/uncertainty, significant associations disappeared in all conditions except the four-minute condition. This finding, however, was not evidenced in a follow-up experiment that aimed to directly replicate Experiment 2's results (Tandarich, 2026).

Interestingly, participants in the 32-minute task were relatively accurate in their estimates (ratio = 1.06) in Experiment 2. Recall that when the same visual and memory search task was used in Walker et al. (2022), participants significantly underestimated the 58-minute task (estimation ratio = .73). The results of Experiment 2 and Tandarich (2026) thus indicate that the indifference point for the visual and memory search task used is around half an hour.

Surprisingly, the difficulty of the task influenced participants' accuracy in duration estimates in Experiment 2. This finding was unexpected, given that the two other experiments using the same cognitive task (Experiment 1 of this thesis and Walker et al., 2022) found no impact of difficulty on duration estimates. Therefore, this finding was contrary to my prediction. Difficulty was not expected to impact duration estimates, especially in such lengthy tasks. The strongest effect of task difficulty in the present experiment occurred at four minutes. Yet, in Experiment 1, there was absolutely no effect of task difficulty at four minutes. This was thus further investigated in Tandarich (2026), and the effect was not replicated despite using the exact

same experimental methodology. The failed attempt to directly replicate the results suggests that the effect of task difficulty found in Experiment 2 was probably a Type-1 error.

Furthermore, I did predict that several task qualities would influence participants' uncertainty in Experiment 2. This prediction came from the observation in Walker (2019) that it is not "cognitive load" that influences the pace of time, but the affective appraisal of the experience that accompanies tasks of varying difficulty. The results of the regression analysis indicated that task duration and participants' reported boredom levels predicted their level of uncertainty. The same was true for their PoTJs. That is, boredom was the only appraisal to significantly predict time perception, above and beyond task difficulty and duration, when measuring IU and PoTJ. However, because the subjective task difficulty and level of distraction in this task were seen as potentially important factors (marginally significant regression results), Experiment 3 subsequently tested the relation between boredom and time perception, while also including subjective difficulty and distraction as additional exploratory variables.

Experiment 3: Adjustments in Time Estimation

The third experiment once again investigated the relation between duration estimates and PoTJs. The goal of this experiment was to test whether PoTJs add any explanatory power to traditional models of time perception and distortion. Rather than using a self-report questionnaire like in Experiment 2, this experiment tested whether drawing attention to the passage of time directly influenced duration estimates. Half the participants in this experiment were thus asked to provide a PoTJ *before* their duration estimate. The other half provided a PoTJ *after* the estimate.

Research Questions and Hypotheses

Q7: Does directing awareness toward the pace of subjective time influence the accuracy or uncertainty of a duration estimate?

H7: I predicted that asking for a PoTJ first (rather than second) would draw attention to the pace of time, making people less certain of their estimates, and resulting in larger standard errors in their estimates.

Q8: Does attention to time influence the accuracy of a duration estimate?

H8: Because I implemented a four-minute task in this experiment, I expected that participants who received prospective instructions would overestimate the task's duration more than those who received retrospective instructions (replicating the result in Experiment 1).

Q9: Does drawing attention to the pace of time interact with a person's level of boredom to influence their PoTJs?

H9: Drawing attention to the pace of time by asking for a PoTJ first will lead to a more pronounced overestimation of time for those who found the task more boring.

Experiment 3 Method

For this experiment, I implemented the four-minute (40-trial), consistent mapping version of the visual and memory search task for all participants. I selected this condition because PoTJs, engagement, and boredom ratings were quite variable in Walker (2019) (see Figures I.1 and I.2 in Appendix I). It was thus possible to examine the relation between these variables across estimation paradigms (prospective vs. retrospective) and the potential bias introduced by the order of the time perception questions. The following experiment was preregistered on the Open Science Framework (OSF) at https://osf.io/jnw6d/.

Participants. Two hundred and seventy participants with normal or corrected-to-normal vision were recruited for this online experiment between January and March of 2023. Recruitment took place through the University of Ottawa's research participation system (ISPR). Participants completed the experiment via ISPR and received 1.5 points toward research

participation credits because they were told the experiment could last up to 90 minutes but could end at any point before this maximum was reached (replicating the instructions of Experiments 1 and 2). The University of Ottawa Research Ethics Board approved this experiment (#H-10-22-8464).

Design. This experiment was conducted online. Participants were randomly assigned to either a prospective or a retrospective condition; thus, only half were expected to pay attention to time throughout the concurrent task. At the end of the task, half of the participants were asked to provide a PoTJ first, whereas the other half were asked to provide a duration estimate first. This configuration yielded a 2 (prospective vs. retrospective) × 2 (order of time perception questions) between-subjects design.

As in experiment 2, the task was programmed in Qualtrics as a consistent-mapping (low workload) version of the visual and memory search task. Time-related questions automatically appeared on screen after completion of the visual and memory search task.

Procedure. The procedure for Experiment 3 was the same as in Experiment 1, except that all participants performed the consistent-mapping version of the visual and memory search task. Moreover, all participants were given a four-minute task. Therefore, the task duration was not manipulated in this experiment. Participants in the retrospective condition were told that this was an experiment investigating the impact of distractions on their task performance and that they were assigned to the "no distractions" group. They were thus asked to remove all electronics, music, and any access to the time, as these are all potential sources of distraction. These instructions were communicated via video.

Based on the results of Experiment 2's exploratory analyses, participants were asked to rate their level of boredom, the subjective difficulty of the task, and the amount of distraction

present in their environment, in addition to the standard questions about the duration of the task and the pace of psychological time. At the end of the experiment, participants were told the actual duration of the task and asked whether they were surprised by the true task duration ("yes" or "no") to gauge how accurately they perceived themselves to be.

Experiment 3 Results

Initial Data Cleaning and Final Demographics. All the participants reported following the instructions to complete the experiment using a keyboard. Of the 270 participants who completed the experiment, 21 were excluded from analysis because they reported checking the time throughout the task, and five were removed because they reported knowing before beginning the task that they would be asked about their perception of time, even though they were assigned to a retrospective condition. In the retrospective condition, two participants did not sign the secondary consent form following the reveal of the experiment's true purpose, and two other participants completed the task twice (duplicate participant numbers in the data file). All four of these participants were excluded from analysis. Two participants reported that a friend in the room was distracting them from the experiment. These participants were thus removed for not following the instructions to complete the experiment alone in a quiet space.

Finally, I included a screening question for drug and alcohol use. No participants reported being under the influence of cannabis or alcohol during the experiment. In an open-ended question asking participants if anything else may have affected their time perception, 10.9% of the sample offered responses. One person cited a past concussion, six cited ADHD, two cited chronic pain, seven cited stress, one cited nicotine use, one cited caffeine use, four cited fatigue/tiredness, one cited a runny nose, and three cited mind-wondering as having a potential

effect on their time perception. As these conditions were not pre-registered exclusion criteria, these participants remained in the final sample.

I then examined the remaining 238 participants' performance on the visual and memory search task for outliers. Participants were removed from the analysis if their accuracy on the visual and memory search task was three SDs below the mean of their group. Such low performance was interpreted as a lack of engagement with the task and thus as a failure to participate in the experiment. Six participants had outlying performance and were thus excluded from the analysis, resulting in a final sample of 232 participants (ranging from 55 to 64 per group). One hundred eighty-four participants were female (79%), 45 were male, one was transgender male, one was non-binary, and one was gender fluid. Their ages ranged from 16 to 45 years old (M = 19).

Manipulation Check. I then examined performance on the visual and memory search tasks to ensure there were no differences in task difficulty across groups as task difficulty was not manipulated in this experiment. I conducted this analysis to ensure that all groups performed the task with the same level of accuracy and similar RTs. Therefore, any conclusions about their performance could not be attributed to differences in task difficulty across groups. All groups performed the same task for the same duration, and the results indicated that they achieved similar accuracy and RTs (see Table 8). There was no significant difference in accuracy across groups: $F(3, 228) = 1.01$, $p < .39$.

Table 8.

Group mean visual and memory search accuracy (percentage) and response times (milliseconds) with square brackets denoting the 95% confidence interval of the mean.

	Prospective		**Retrospective**	
Group	**PoTJ first**	**PoTJ second**	**PoTJ first**	**PoTJ second**
Accuracy	96.9 [95.9, 98.0]	97.3 [96.4, 98.2]	98.0 [97.2, 98.8]	97.4 [96.5, 98.3]
RT	877.2 [833.9, 920.5]	875.7 [818.8, 932.5]	826.7 [779.9, 873.5]	873.1 [827.3, 918.9]

Duration Estimation Results. The following analyses were conducted to investigate the effects of the estimation paradigm and the order of the time perception questions on participants' perception of time: In keeping with the analytic procedures used in Experiments 1 and 2, I first examined participants' duration estimates. A 2 (prospective vs. retrospective) × 2 (order of questions) between-subject ANOVA was conducted on ratio and IU. In addition, I included an additional outcome variable: the Absolute Standard Error (ASE). ASE was calculated by taking the absolute difference between a time estimate and the task's duration ($E_D - T_D$) and dividing this by the task's duration (T_D).

$$\text{ASE} = \text{absolute}\ (E_D - T_D) / T_D \quad (3)$$

The ASE can be used to determine how far the estimate was from the actual task duration. Instead of simply determining whether the duration estimate was accurate or inaccurate, as with the estimation ratio, the ASE provides additional information about the degree of inaccuracy present in the response. The ASE was also subjected to the same 2 × 2 ANOVA.

I included the ASE variable because I was interested in whether the accuracy of a duration estimate is influenced by drawing attention toward the passage of time. Therefore, regardless of whether participants over- or underestimate the task's duration, I predicted that the degree of over- or underestimation would change depending on the order of the time judgement questions.

Moreover, I expected to replicate the effects of boredom on PoTJs found in Experiment 2. However, I also predicted that the order of time-related questions would impact PoTJs. Therefore, I regressed boredom ratings on PoTJs and then entered the order of time-related questions in as an interaction term.

Duration Estimates. Table 9 shows participants' duration estimates in minutes, with outliers removed and Figure 16 shows the results of participants' duration estimates transformed into ratios. Participants who provided a duration estimate that was three SDs above or below the mean of their group were removed from the analysis. This resulted in the removal of data from three participants. Levine's test was not significant, $F(3, 225) = 2.51$, $p = .86$, meaning that there was no violation of the assumption for homogeneity of variance between groups.

Table 9.
Group mean duration estimates (as well as group mean minimum and maximum estimates) in minutes with square brackets donating the 95% confidence interval f the mean.

	Prospective		**Retrospective**	
Group	**PoTJ first**	**PoTJ second**	**PoTJ first**	**PoTJ second**
Mean Estimate	7.8 [7.0, 8.5]	7.4 [6.6, 8.2]	6.5 [5.7, 7.3]	7.1 [6.3, 7.9]
Minimum	5.0 [4.3, 5.7]	4.9 [4.1, 5.6]	4.4 [3.6, 5.2]	4.9 [4.2, 5.6]
Maximum	10.8 [9.4, 12.2]	9.9 [8.5, 11.2]	9.3 [8.0, 10.6]	8.9 [8.9, 7.7, 10.0]

Note. Mean minimum and mean maximum estimates represent the internal uncertainty around the group's mean.

There was no interaction between paradigm and question order in this experiment $F(1, 255) = 1.35$, $p = .25$. However, the ANOVA revealed a significant main effect of paradigm, $F(1, 225) = 4.08$, $p = .045$, $\eta_p^2 = .02$. On average, and as predicted, participants overestimated the duration of the prospective task to a greater degree (*Mean ratio* = 1.90, *SD* = .74 [1.76, 2.04]) compared to the retrospective task (*Mean ratio* = 1.70, *SD* = .77 [1.56, 1.84]), with participants in the prospective group stating that the four-minute took 7.62 minutes and the retrospective group estimating that it took 6.80 minutes to complete. These finding replicate Experiment 1, in which prospective estimates were greater than retrospective ones at four minutes. However, it should be noted that the effect size is small. There was no effect of question order, $F(1, 255) = .07$, $p = .79$.

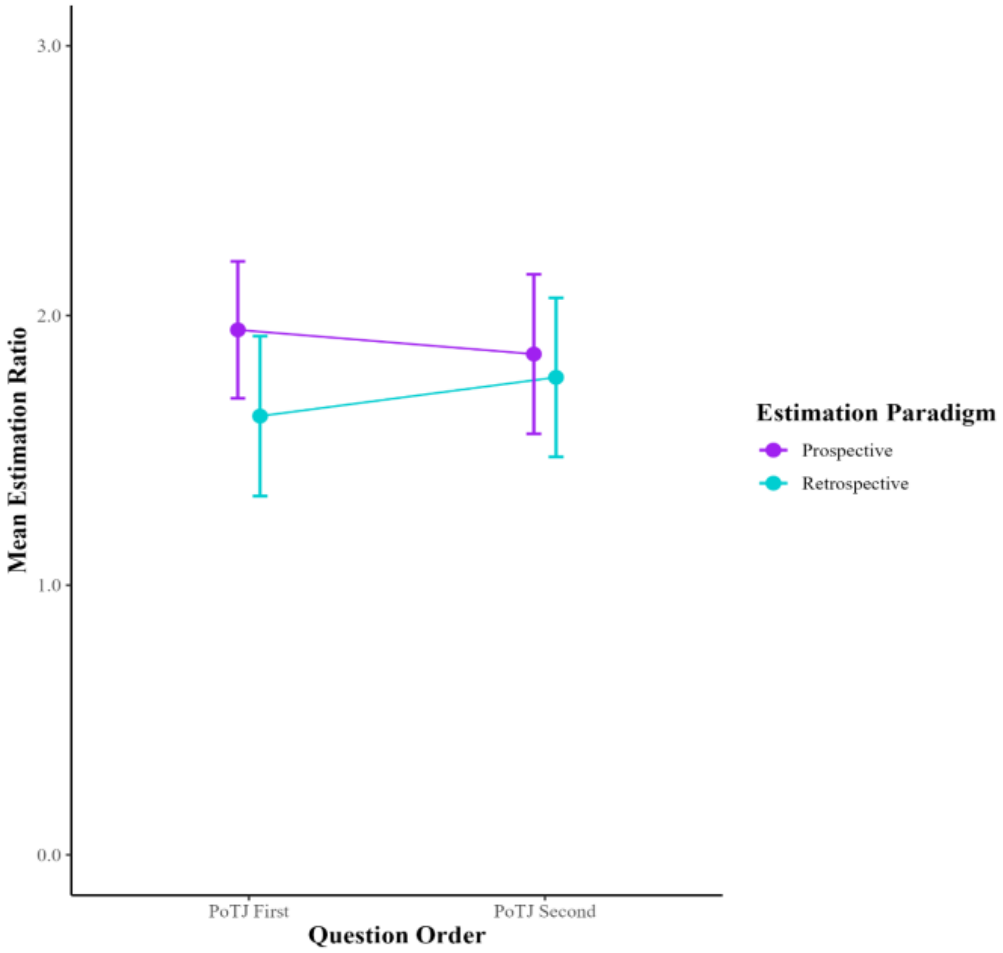


Figure 16. Mean time estimation ratios (participants' duration estimate over the actual task duration). Difference-adjusted error bars show the 95% confidence intervals of the mean.

Absolute Standard Error. To determine how far the estimates deviated from real time, ASE was analyzed next. Figure 17 shows the results of participants' ASEs. Levine's test for homogeneity of variance between groups was not significant, $F(3, 225) = 1.28$, $p = .28$. There was no interaction found, nor were there any significant main effects of paradigm and question order: ps > .09. By changing the scale from ratio (a measure of over or underestimation) to magnitude (with 0 representing the actual task's duration), the paradigm effect disappeared. In other words, prospective and retrospective estimates were equally overestimated in absolute terms.

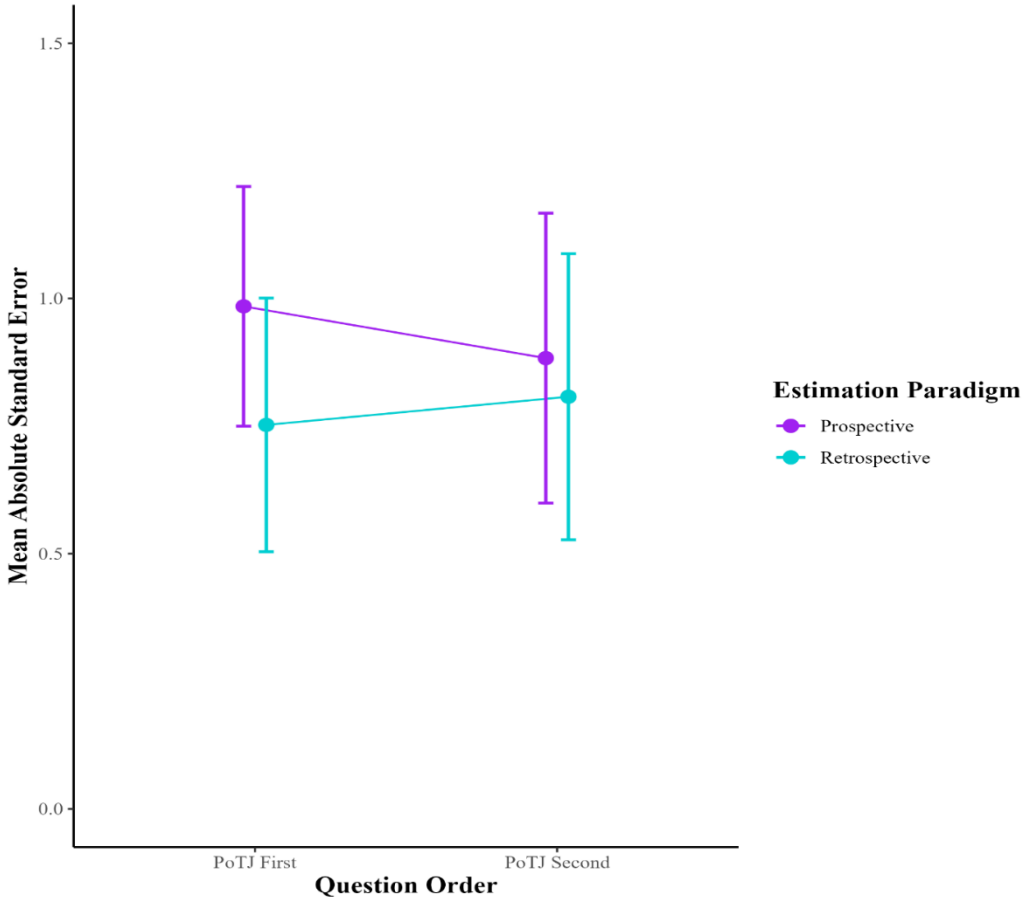


Figure 17. Absolute standard errors (the absolute difference between the participants' duration estimate and the actual task duration, divided by the actual task duration). Difference-adjusted error bars show the 95% confidence intervals of the mean.

Internal Uncertainty. Uncertainty in participants' time estimates was also measured and is shown in Figure 18. Anyone's responses that 1) exceeded three SDs above or below the mean of their group, and 2) contained a maximum estimate that was smaller than the minimum estimate, were removed from the following analyses. This resulted in the removal of eight participants. Error variance was equal across groups, $F(3, 220) = 2.29$, $p = .08$.

Like ratio, there was no two-way interaction found between task paradigm and question order, $F(1, 220) < .001$, $p = .99$. However, there was a significant main effect of paradigm, $F(1, 220) = 4.91$, $p = .03$, $\eta_p^2 = .02$ and the effect of question order was marginally significant, $F(1, 220) = 3.53$, $p = .06$, $\eta_p^2 = .02$. In this experiment, the average IU of the prospective group

(*M* = 1.37, *SD* = .92 [1.12, 1.50]) was larger than the retrospective group (*M* = 1.11, *SD* = .81 [.96, 1.35]). Furthermore, although not reaching statistical significance, the average IU appears to be higher when the PoTJ was presented first (*M* = 1.36, *SD* = .94, [1.12, 1.50]) rather than second (*M* = 1.13, *SD* = .79 [.96, 1.34]). Therefore, participants were less certain about their estimates when instructed to pay attention to the time leading up to the task (prospective condition). Additionally, there is evidence that directing one's attention to the feeling of time passing before making a judgment reduces certainty in their estimates. Therefore, this marginal effect should be further investigated in future research.

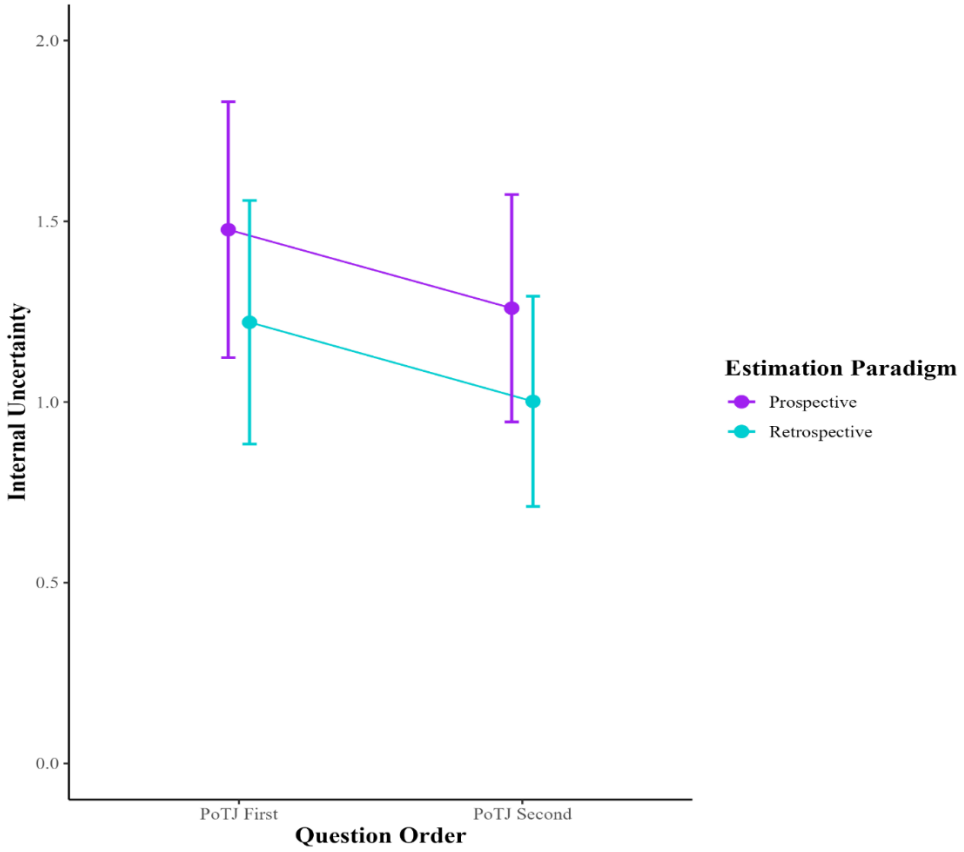


Figure 18. Internal uncertainty (the difference between the participants' maximum and minimum time estimates over the actual task duration). Difference-adjusted error bars show the 95% confidence intervals of the mean.

Subjective Experience. To explore whether participants' estimates were related to the feeling of time passing, correlations between Ratios and PoTJs were analyzed. The correlations are presented in Table 10. There was no significant relation between these two variables in Experiment 3 (r = -.09, p = .18). Therefore, just like the direct replication of Experiment 2 by Tandarich (2026), the correlation between PoTJ and ratio found in Experiment 2's four-minute condition failed to replicate. Of note, this experiment had much more power (N = 229) than the examination of the four-minute conditions in both Experiment 1 (N = 177) and Experiment 2 (N = 76).

PoTJs did correlate, however, with participants' level of engagement (r = .37, p = < .001), boredom (r = -.30, p < .001), subjective appraisal of the task's difficulty (r = .16, p = .02), and their level of distraction (r = - .19, p = .003). Meanwhile, the ratio results did not correlate with any of these exploratory variables (ps < .16) except for a potentially marginally significant relation with boredom (r = .12, p = .065; See Table 10).

Table 10.

Correlations among the six variables of interest

	1	2	3	4	5
1. Ratio	----				
2. PoTJ	-.09	----			
3. Engagement	-.09	.37**	----		
4. Boredom	.10	-.30**	-.36**	----	
5. Subjective Difficulty	.09	.16*	.10	-.16*	----
6. Distraction	.08	-.19**	-.46**	.25**	.17*

Note. * p < .01. ** p < .001.

As in Experiment 2, these variables were entered into a regression to further explore their relationship with PoTJs. However, this time, instead of task difficulty and task duration, the main

independent variables of paradigm and question order were entered as a first step. Then, engagement, boredom, subjective difficulty, and distraction were entered (see Table 11).

Table 11.

Linear model of predictors of PoTJ

	***b* (95% CI)**	***SE***	**β**	***t***	***p***
Step 1					
Constant	4.11 (3.40, 4.83)	.37		11.28	< .001
Paradigm	-1.87 (-.63, .26)	.23	-.06	-.83	.41
Question order	-.42 (-.87, .02)	.23	-.12	-1.88	.06
Step 2					
Constant	3.32 (1.92, 4.71)	.71		4.69	< .001
Paradigm	-.31 (-.71, .11)	.21	-.09	-1.47	.14
Question order	-.39 (-.79, .01)	.20	-.11	-1.92	.06
Engagement	.27 (.13, .40)	.07	.28	3.95	< .001
Boredom	-.14 (-.26, -.03)	.06	-.16	-2.47	.01
Subjective difficulty	.16 (-.003, .32)	.08	.12	1.93	.06
Distraction	-.08 (-.25, .08)	.09	-.07	-.99	.32

Note. $R^2 = .02$ for Step 1; $\Delta R^2 = .19$ for Step 2 ($p < .001$).

The results of the regression suggest that the estimation paradigm (prospective vs. retrospective) did not impact PoTJ results. However, in both models, the order of time perception questions may have a marginal effect on PoTJs, although this effect did not reach statistical significance (*p*s = .06). Engagement and boredom were both significant predictors of PoTJs. These variables added predictive power to the model, thereby explaining differences in the PoTJ results above and beyond what would be explained by paradigm and question order. Finally, just like in Experiment 2, the subjective difficulty of the task had a potential marginal effect on PoTJs. Therefore, participants' appraisal of the task's qualities (i.e., how engaging, boring, and difficult it felt) seemed to have affected the subjective pace of time, with engagement and boredom having a clearer impact on the pace of time than the subjective difficulty of the task.

Compensatory mechanism. A main hypothesis of interest for this experiment was that drawing attention to time by asking for a PoTJ first would lead to greater overestimation among

those who found the task boring. I therefore ran a regression analysis on participants' estimation ratios, with boredom and question order entered in the model, along with their interaction term. The results revealed a marginally significant interaction between participants' boredom levels and question order (Table 12). Moreover, boredom appears to be a statistically significant predictor of estimation ratio in this model. Therefore, it is possible that reflecting on the pace of time before providing a duration estimate impacts the accuracy of that estimate, depending on the level of boredom (Hypothesis 9). However, this result requires further investigation in future research, since the effect did not reach statistical significance. What is clear, however, is that participants' level of boredom predicted their estimate accuracy in an easy, four-minute task.

Table 12.

Linear model of predictors of ratio

	***b* (95% CI)**	***SE***	**β**	***t***	***p***
Step 1					
Constant	1.81 (1.67, 1.95)	.07		25.71	< .001
Question order	.01 (-.19, .21)	.10	.01	.08	.94
Boredom	-.08 (.01, .15)	.04	.21	2.31	.02
Boredom × Question order	-.09 (-.20, .01)	.05	-.16	-1.80	.07

Note. $R^2 = .02$

As an exploratory step, I reran the same regression as above, this time with PoTJ as the outcome variable (Table 13). Boredom was once again the only significant predictor in the model, and question order showed a marginally significant effect. There was no interaction between boredom level and question order. The results of these two regression models suggest that time perception is clearly influenced by people's level of boredom during a visual and memory search task, whether measured via a duration estimate or a PoTJ question when task difficulty and duration are held constant.

Table 13.

Linear model of predictors of PoTJ

	***b* (95% CI)**	***SE***	**β**	***t***	***p***
Step 1					
Constant	3.82 (3.53, 4.12)	.25		25.48	< .001
Question order	-.40 (-.82, .03)	.22	-.12	-1.85	.07
Boredom	-.19 (-.34, -.04)	.08	-.21	-2.44	.02
Boredom × Question order	-.14 (-.36, .08)	.11	-.11	-1.28	.20

Note. $R^2 = .11$

Exploratory Analyses. Because some evidence suggested that the order of time perception questions affects participants' estimates of uncertainty, I examined whether there were group differences in the frequency with which participants endorsed surprise when learning the true duration of the task. Therefore, at the end of the experiment, participants were informed of the actual task duration and asked whether they were surprised by it ("yes" or "no"). Their responses are depicted in Figure 19. One hundred and nineteen participants answered the PoTJ question before providing a duration estimate, and 113 answered the PoTJ question after their estimate. In the former condition, 85 (71.4%) participants reported being surprised by the actual duration of the task (across both paradigms). In the latter condition, 67 (59.3%) participants reported being surprised. An analysis of proportions (ANOPA; Laurencelle & Cousineau, 2023) was conducted to test whether the difference in surprise between groups was significant.

A significant main effect of question order was found, $F(1, \infty) = 3.73$, $p = .053$. Asking participants to reflect on the pace of time before they provided a duration estimate did result in greater surprise when the task's duration was revealed. This result suggests that directing participants' attention to the internal pace of time may impact their insight, even though their duration estimate accuracy was not affected by this manipulation.

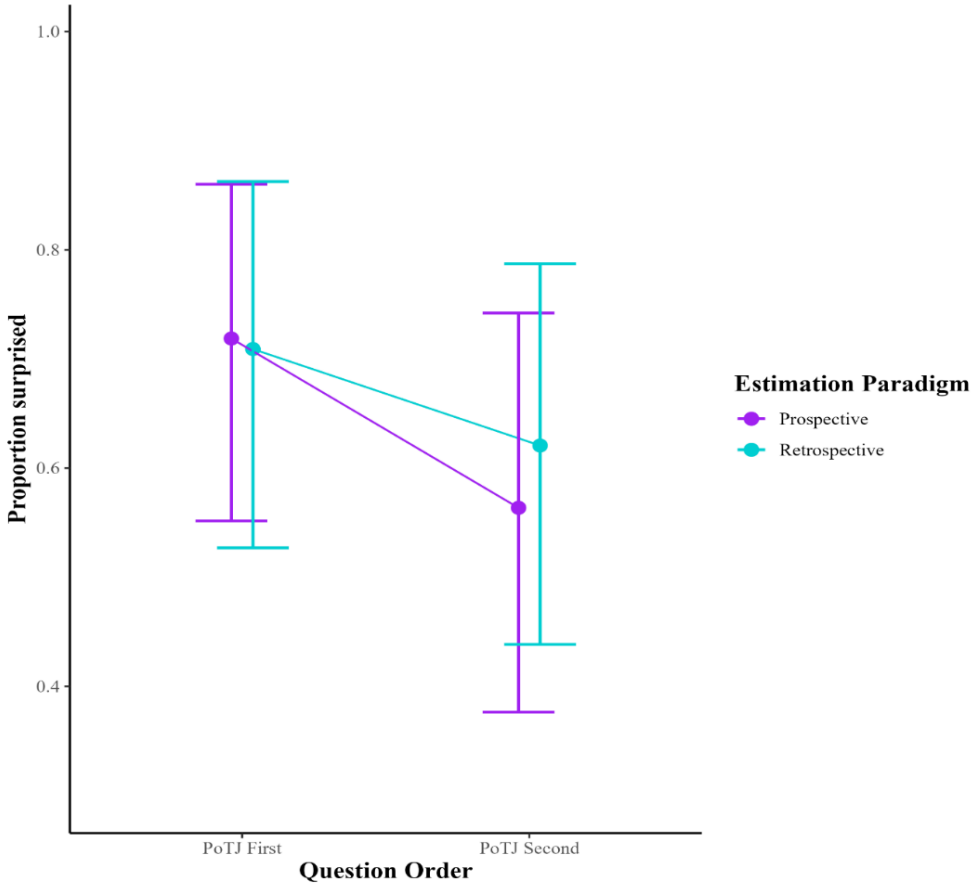


Figure 19. Proportion of participants out of 232 that endorsed being surprised by the length of the task (four minutes). Error bars show the 95% confidence intervals of the mean.

The above result is especially interesting when considering group differences between participants in the prospective and retrospective paradigms. Although participants in the prospective condition overestimated the task's duration to a greater degree and provided a wider range of responses (i.e., greater uncertainty), they were equally surprised by the task's duration as participants in the retrospective condition. That is, both groups endorsed the same level of surprise with 64.7% saying "yes" in the prospective condition and 66.4% saying "yes" in the retrospective condition (that is, a lack of main effect of estimation paradigm, $F(1, \infty) = 0.13$, $p = .72$). Although half of the participants knew that they would provide details about their experience of time in this experiment, they were similarly surprised by the task duration at the

end of the experiment. Moreover, there was no interaction found between question order and paradigm [$F(1, \infty) = 0.27$, $p = .60$] on the proportion of surprise. In conclusion, manipulating the order in which the time perception questions appeared in the questionnaire (duration estimate vs. PoTJ) had a significant impact on participants' level of surprise, but informing participants about the impending time judgement before beginning the task did not.

Experiment 3 Discussion

I predicted that drawing attention to the subjective pace of time would bias people's estimates. Specifically, by asking for a PoTJ before a duration estimate, I expected to find more pronounced uncertainty and larger standard errors in their duration estimates. However, I found no such result. The order of time perception questions did not affect people's estimate accuracy, although there was some evidence to suggest a potential effect on uncertainty. That is, the order of time perception questions did have a marginal (not quite reaching statistical significance) effect on the range of people's time estimates. That is, IU was potentially higher when the PoTJ was presented first rather than second. Moreover, as an exploratory step, I asked participants to indicate how surprised they were by the actual length when the task duration was revealed at the end of the experiment. Although directing people's attention to the psychological pace of time did not yield clear differences in estimation accuracy, people reported greater surprise when a PoTJ question was presented first in the questionnaire.

Furthermore, participants were less certain of their estimates when told that they would be estimating the duration of the task (prospective condition). This finding was also true for their estimation accuracy, with the prospective paradigm yielding significantly larger estimates than the retrospective one (although both groups overestimated the task duration on average). However, the estimation paradigm was not a significant predictor of PoTJs. Instead, engagement

and boredom were the only significant predictors of PoTJ results, with the order of questions and the subjective difficulty of the task yielding marginally significant results.

Finally, I predicted that drawing attention to the pace of time by first asking for a PoTJ would lead to greater overestimation of the task's duration among those who found the task more boring. There was some evidence to support this hypothesis in this experiment. However, the results did not reach statistical significance, so further research would help clarify this. Moreover, no correlation was found between PoTJ and duration estimate accuracy. Rather, participants' boredom level in this experiment affected both duration estimates and PoTJs independently, regardless of whether they reported their PoTJ before or after their duration estimate.

CHAPTER 3: THE FINDINGS

The broad aim of this research was to help update the most prominent cognitive theories of time perception by empirically investigating psychological time distortions across task durations. This aim was addressed in two ways. First, estimation accuracy and certainty were assessed across task difficulty levels, two estimation paradigms (prospective and retrospective), and a range of experimental durations. Second, participants' subjective experience of time (PoTJs) was systematically measured and compared to the duration estimate results. Furthermore, concerns about the replicability of psychological science have highlighted the importance of demonstrating consistency across studies (Open Science Collaboration, 2015; Zwaan et al., 2018). In response, this thesis systematically examined duration estimates, internal uncertainty, and PoTJs using the exact same cognitive task across multiple experiments. Doing so strengthened the integrity of the findings.

To briefly review, the AGM is a widely cited cognitive model that predicts duration-estimation performance under prospective conditions. Grondin (2025) describes the AGM as an internal clock-like mechanism akin to a counter or a pacemaker. Attention is a key factor in the accuracy of this mechanism. Attending to the passage of time while also performing a secondary cognitive task is most challenging if both activities draw on limited resources from a shared pool (see Wickens, 2008, for a review). Diverting attention away from time thus effectively shortens the perceived duration because the cognitive counter misses temporal information. This model is evidenced by interference effects, which are consistently observed in dual-task paradigms lasting several seconds (Brown, 1997).

In the retrospective context, memory plays a more important role than attention. That is, while the accuracy of an internal clock is influenced by the availability of attentional resources in

prospective paradigms, the accuracy of retrospective memory is altered by the availability of recalled contextual cues (Block & Zakay, 2008). People thus typically judge intervals to be longer at the beginning of a task because context changes rapidly at the onset of an experiment (Hintzman et al., 1973). Fewer events are encoded in memory over time as the context loses its novelty. In this thesis, manipulating the estimation paradigm yielded results that fit well within both popular frameworks. However, the results also suggest areas where these frameworks can be modified to better account for duration estimation performance in prolonged tasks.

Overall, and discussed throughout this final chapter, this thesis makes three contributions to the study of psychological time distortions. First, the results of Experiments 1 and 3 provide evidence that the classic paradigm effect extends to longer durations than typically examined. Second, this thesis provides evidence for a shift in the mechanisms underlying duration estimation as task duration increases. However, because attention was not directly measured, this evidence is based on established theoretical accounts (discussed below) rather than process-level evidence. Third, the experiments show that duration estimates and PoTJs are the product of partially overlapping but interacting systems. Whereas attentional and contextual factors are thought to primarily shape duration estimates, PoTJs are more closely related to internal experiences like boredom. Together, these findings support a revised, integrative account in which attention, memory, and internal states contribute to time perception during prolonged tasks.

How Duration Estimates Change Over Time

A Paradigm Effect at Long Durations

The experiments in this thesis addressed an important methodological gap by using the same visual and memory search task across experiments of different lengths, in keeping with the

methodology employed by Walker et al. (2022). Most direct comparisons between retrospective and prospective time estimation paradigms have focused on short durations (e.g., tasks lasting less than two minutes, Block & Zakay, 1997). Experiments that have implemented tasks exceeding two minutes have found mixed results (Tobin & Grondin, 2009; Bisson et al., 2012; Kikkawa, 1983; Tobin et al., 2010; Tobin & Grondin, 2009). Notably, these longer experiments have often used heterogeneous tasks (i.e., visual search booklets, reading, playing video games, or watching a film). The variability in both duration and selected tasks has thus made it difficult to determine whether the paradigm effect generalizes to longer intervals.

In Experiment 1, retrospective duration estimates were greater (overestimated to a greater degree) than prospective estimates at 30 seconds. That is, regardless of task difficulty, participants significantly overestimated the duration of the 30-second retrospective condition. Prospective estimates, although also overestimated, were slightly closer to real time, perhaps because participants engaged in a dual-task condition. Unlike the retrospective group, prospective group participants had to divide their attention between the visual and memory search task and their internal timekeeping. As expected for a divided-attention condition, this effectively "shortened" their responses relative to the single-task retrospective condition, blunting their estimates.

Prospective estimates were then significantly overestimated relative to those of the retrospective group by the time the task reached four minutes. This interaction may be due to the monotonous nature of the visual and memory search task. The novelty of the task probably wore off quickly with its repetitive nature at both difficulty levels. As this occurred, participants in the prospective condition had more capacity to notice time, and participants in the retrospective condition had fewer contextual changes to recall when asked to provide an estimate. I thus found

a cross-over interaction between estimation paradigm and task duration in Experiment 1. The results were then replicated in Experiment 3, in which prospective estimates were once again greater than retrospective estimates at four minutes.

Taken together with the significant paradigm effect in Walker et al. (2022)'s eight-minute condition using the same task, contemporary theories of time perception do adequately explain duration estimation performance in the examined visual and memory search task, at least when it spans four to eight minutes. However, because the present work relied on a single paradigm, it remains unclear whether this pattern would generalize to tasks of varying structure, novelty, or ecological validity. As mentioned, contemporary theories focus on differences in dual-task vs. single-task performance and on context changes recalled over time. As these findings are based on a controlled visual search task, these conclusions may not generalize beyond this paradigm. Moreover, because attention was not directly measured, the role of attentional allocation is inferred rather than directly observed.

Importantly, contradictory results regarding the effect of task difficulty emerged across my first two experiments. These findings suggest that existing models of time perception may be insufficient to *fully* account for the lack of interaction between task paradigm and difficulty at longer intervals.

The Effect of Task Difficulty at Long Durations

In Experiment 1, the task difficulty did not affect participants' duration estimates. I predicted that varying difficulty levels would result in a higher information-processing load, thereby diverting attention away from time on the more challenging version of the visual and memory search task. I predicted that this manipulation would result in shorter estimates than those of participants assigned to the easier version of this task. Moreover, in the retrospective

condition, I hypothesized that the rapidly changing information in the varied-mapping (more difficult) visual search condition would result in greater overestimation than in the monotonous and repetitive consistent-mapping (easy) condition. I also predicted that the effect of task difficulty would attenuate over time, providing evidence that people offload their attention to time as duration increases. This manipulation of task difficulty and duration would help determine whether there exists a boundary of attentional release. These predictions were not supported by the results of Experiment 1. Yet in Experiment 2, the task difficulty did significantly affect estimates at four minutes. Curiously, the effect was opposite of what is typically observed.

All participants in Experiment 2 completed a prospective timing task and were instructed to divide their attention between time-keeping and visual search. If the diversion of people's attention results in fewer accumulated temporal pulses, as predicted by the AGM, then the prospective estimates in this experiment should have been shorter with increased task difficulty. Instead, estimates in this experiment behaved similarly to those in retrospective paradigms, where estimates *increased* with heightened task difficulty. Because attention was not directly measured, however, this interpretation assumes that the difficulty manipulation successfully altered attentional allocation.

Since Experiment 2 was conducted online, greater variability in the participants' environments may have influenced the extent to which they were attentive toward time. Compared to the high degree of experimental control of Experiment 1, this variability may have introduced additional noise into the data. This noise either produced a spurious effect of task difficulty, or it may have reflected an important difference in time perception between home and the lab contexts. To evaluate the robustness of the effect, a direct follow-up experiment was

conducted by Tandarich (2026) using the exact methodology of Experiment 2. The results showed that the effect of task difficulty did not replicate. There is thus insufficient evidence that task difficulty affects duration estimates at long durations, at least in a visual and memory search task. Nevertheless, one robust finding emerged across Experiments 1 and 2 (and Tandarich's direct replication): the accuracy of duration estimates systematically changed as a function of task duration.

"When" are Estimates Most Accurate?

Across all three experiments in this thesis, time was easily distorted by engaging in a visual and memory search task. Even in Experiment 3's easy task condition, participants overestimated the duration of a four-minute task by approximately a factor of two. This tendency to overestimate task duration was replicated across all three experiments. However, a pattern also emerged in which participants were more accurate at estimating the time as the duration increased (group overestimation decreased over time).

A duration estimate that aligns perfectly with the actual task duration is called the indifference point. This indifference point is thought to differ across experiments (Eisler et al., 2008). Experiment 2, for example, found that participants were relatively accurate in their estimates at 32 minutes, especially compared to the degree of overestimation found in the four-minute task. This effect is not surprising, considering Walker et al. (2022) found that participants overestimated the eight-minute task and underestimated the 58-minute task. Theoretically, the indifference point for this type of visual search task should lie between eight and 58 minutes, as was evidenced by Experiment 2 of this thesis.

Similarly, Tobin et al. (2010) and Droit-Volet et al. (2018) found that duration estimates were most accurate around half an hour. In Tobin et al., they found that estimates were most

accurate around 35 minutes compared to their other groups. In Droit-Volet et al., participants were most accurate around 28 minutes, compared with their other groups. Although neither of these experiments used a visual and memory search task, they nevertheless found a pattern of results like that of the current thesis. More recently, in an examination of retrospective time estimation testing a wide range of intervals from five to nine minutes, Balci et al. (2023) found that in a large sample of 24,500 participants, people overestimated how long it took them to complete questionnaires when the task was less than 15 minutes. However, they underestimated this task when it took longer than 15 minutes. Their estimates were most accurate at around 15 minutes, but the between-subject variability in estimates decreased as a function of time, reaching the lower asymptote around 30 minutes.

Taken together, with more research using longer experiments, we are beginning to find evidence not only for the occurrence of time distortions but also for flawless time perception. Several vital functions depend on psychological timing, like planning and performing daily activities (Zakay, 2014). Understanding the conditions under which our perception of time aligns with reality is especially important for tasks that require accurate time management. If we know that we tend to overestimate short tasks (as seen, for example, in Experiment 1) and underestimate very long ones (e.g., close to one hour; Walker et al. 2022), then breaking tasks into 15–30-minute intervals might help us regulate our behaviour more effectively.

How Uncertainty and PoTJs Compare to Duration Estimates

As stated in Walker et al. (2022), the visual and memory search task used in this experiment "offers insight into time estimation ability in a type of task that requires repetitive and automatic stimulus–response processing" (p. 849). Data entry tasks, scanning and labelling items in a retail environment, visual scanning in security settings, and repetitive tasks in video

games are all examples of this type of automatic stimulus-response processing. These types of repetitive settings are often those in which time *feels* like it shifts. Importantly, people's duration estimates may not always reflect the protraction or contraction of psychological time.

As seen, duration estimates can sometimes fail to capture fluctuations in the experience of time, especially when processing demands change (Wearden, 2008). For example, participants may be aware of temporal distortions within a task and thus compensate for fluctuations in time perception when providing their estimates. This compensation might be observed when measuring the uncertainty of their estimates (e.g., Walker et al., 2022). Likewise, asking participants to report on their internal pace of psychological time rather than to produce an estimate based on formalized clock units can reveal hidden temporal distortions that are not always evident in verbal estimates alone (Droit-Volet et al., 2018).

Internal Uncertainty

As in Walker et al. (2022), the task duration reliably affected estimation uncertainty in my first two experiments. Relative to the duration under investigation, participants provided larger ranges for briefer conditions within each experiment. Thus, across the ranges examined in these two experiments, a pattern emerged: longer tasks had less internal uncertainty. Considering that both experiments found that participants were more accurate in their estimates as task duration increased, this provides evidence that participants were aware of their psychological time distortions (i.e., overestimation) and thus felt less confident in their responses when they were less accurate.

In Experiment 2, participants were less certain about their duration estimates in the *difficult* four-minute condition compared to the *easy* four-minute condition, but this finding did not replicate (Tandarich, 2026). Recall that this is the only condition in Experiment 2 in which

task difficulty did affect people's duration estimate accuracy. This finding thus highlights that participants were aware of a potential distortion in Experiment 2's four-minute task (indicating that they were less certain in their guesses). Furthermore, participants were less certain about their estimates in the prospective condition than in the retrospective condition in Experiment 3. Perhaps instructing them to focus on time made them less confident in their responses. This finding aligns well with the eight-minute condition in Walker et al. (2022), in which participants in the prospective condition provided larger estimate ranges than those assigned to the retrospective condition. However, Experiment 1 did not yield the same effect.

While more evidence is needed to determine whether the estimation paradigm impacts people's estimate uncertainty, it nonetheless appears that several experimental manipulations alter the certainty of duration estimates. This finding suggests that distortions of psychological time can be observed by examining the ranges that people provide, rather than simply comparing the accuracy of their initial judgement to the clock.

Passage of Time Judgements

In Experiment 1, estimation accuracy was unaffected by states such as engagement and boredom, whereas PoTJs were correlated with both. I also found that the correlations between these two variables (engagement and boredom) and PoTJs became stronger with increased task duration. This finding provided additional evidence that internal states become increasingly related to the subjective pace of time in prolonged activities. Yet, participants' estimation accuracy was unaffected by how "fast" or "slow" time felt like it passed in Experiment 1 (their accuracy and PoTJ responses were not significantly correlated).

Experiment 2 replicated the effect found in the exploratory analyses of my master's thesis (Walker, 2019). Participants overestimated the shortest task (four minutes) but reported that time

passed quickly in that condition. This behaviour resulted in an apparent correlation between estimation accuracy and PoTJs, as the "fast" condition showed the greatest overestimation. However, the correlation disappeared when examining the relationship between PoTJs and estimation accuracy within each duration group. Although a significant correlation between estimate accuracy and PoTJ was still observed at four minutes, this effect was not replicated in Tandarich (2026) nor in the higher-powered Experiment 3. There was thus no compelling evidence for a direct link between PoTJs and duration estimates with increasing task duration.

Experiment 3 was also an opportunity to empirically test whether participants compensate for the pace of time when formulating their duration estimates. I wanted to know whether people purposefully overestimate the time to account for the *fast* feeling of time passing. I tested this by directing participants' attention to the subjective pace of time before requesting their estimates. The results of Experiment 3 were unfortunately inconclusive. Manipulating the order of time perception questions so that half of the participants reflected on the passage of time before providing their estimate did not affect estimate accuracy. However, there was some evidence of a potential effect on estimation uncertainty, and a clear effect on the degree of surprise they felt when they learned the task's actual duration.

The exploration of "surprise" on PoTJs in Experiment 3 supports the findings of Tanaka and Yotsumoto (2017). They hypothesized that PoTJs arise from a discrepancy between participants' expectations and the actual task duration. They investigated whether a discrepancy between expectations and reality led to changes in PoTJs by assigning participants to N-back tasks ranging from three to seven minutes. The experimenters told all participants that the task would last five minutes, which was true in some cases but false in others. As expected, Tanaka and Yotsumoto found that people rated time as slower when a task was longer than expected.

Perhaps, by directing people's attention to the perceived pace of subjective time in my third experiment, the actual task duration became more salient. That is, by focusing inward and bringing the discrepancy between task length and their expectation to the forefront of their mind, they endorsed higher levels of surprise when the true duration was revealed.

Experiment 3 also provided evidence that, although not directly linked, duration estimates and PoTJs may be the products of separate yet related underlying mechanisms. When the cognitive effort required to complete a task is low, it can lead to the unique emotional state we call boredom. Boredom was a significant predictor of both PoTJs and duration estimation accuracy in my third experiment. This finding also aligns with evidence from Tanaka and Yotsumoto's (2017) experiments and more recent experimental evidence (Droit-Volet, Monier, Larderet, & Martinelli, 2025) in which boredom consistently predicts slower PoTJs.

Situational boredom is experienced when the demands of a task do not require one's attentional resources, such as a monotonous, routine, or non-challenging task that creates very little cognitive stimulation (Zakay, 2014), much like the consistent mapping condition of the task used across all three experiments in this thesis. From an information-processing perspective, both boredom and time perception should vary with the varying cognitive demands of the non-temporal task. The findings in Experiment 3 suggest a potential mechanism in which boredom is simultaneously involved in the pace or flow of psychological time and serves as a heuristic for translating our experience of time into a verbal response.

The results also support the theory that internal states become more salient as the self becomes an increasingly important source of temporal information for deriving a duration estimate (Droit-Volet et al., 2018). Droit-Volet et al. (2018) proposed that rather than time perception resulting from information explicitly obtained from the external environment and

task-specific demands, as common theories suggest, we combine our experience of the environment with our internal appraisals when reflecting on time. Two recently published papers add further support to this theory.

Corroboration with Recent Literature

At the time of data collection for this thesis, which began in 2019, Experiment 1 was the first known study to compare duration estimates and PoTJs across estimation paradigms (prospective vs. retrospective) at longer durations than are typically examined in the literature. During data collection, Martinelli and Droit-Volet published an article (2022a) with a similar experimental structure, yielding similar outcomes. Whereas Experiment 1 of this thesis examined time perception in a visual and memory search task spanning either 30 seconds, one minute, two minutes, or four minutes, Martinelli and Droit-Volet's (2022a) experiment examined time perception when participants observed a neutral image spanning "short durations" (20 seconds, 30 seconds, 45 seconds) or "long durations" (1.33 minutes, 2 minutes, or 3 minutes). Therefore, both experiments compared duration estimates and PoTJs across tasks lasting several seconds to several minutes. The novelty of Experiment 1 of this thesis, and of Martinelli and Droit-Volet's work, is that both experiments compared PoTJs with duration estimates across paradigms.

The exploratory analysis in Experiment 1 is thus the second experiment to show that "the temporal pattern for PoTJs is similar to that found in duration judgement" (Martinelli & Droit-Volet, 2022, p. 7). Specifically, participants rate retrospective conditions as passing more quickly than prospective ones. However, I did not replicate this result in my third experiment (the paradigm was not a significant predictor of PoTJs).

Nevertheless, several important findings from Martinelli and Droit-Volet's (2022a) experiment match the pattern of findings observed throughout this thesis. They found that

attention was the best predictor of short-duration judgments, and they similarly confirmed the existence of a paradigm effect on long-duration estimates. Moreover, they found that the level of boredom reported by participants covaried not only with other emotions but also with the level of attention directed towards the task.

Combined with the results of my experiments, the pace of time as we experience it, and our ability to report elapsed time verbally, all share fundamental processes related to information-processing demands. While the pace of time (PoTJs) depends on affective experiences (like boredom), which experimenters can easily manipulate by changing the task's difficulty, verbal estimates probably depend directly on the attention resources and context changes present in an experiment, which has been repeatedly suggested (Block et al., 2018; Block & Zakay, 2008; Block & Reed 1978; Block & Zakay, 1997; Grondin, 2025; Zakay & Block, 1997). Therefore, duration estimates and PoTJs both relate to the cognitive demands of a situation, though indirectly. In some cases, the cognitive demands of a task might reflect differences in task duration across dual- and single-task paradigms (Experiment 1). In other cases, our sense of time might be sensitive to task-relevant features when they elicit sufficient emotional responses, resulting in a change in the flow of time but not in the estimate.

In fact, another recent article (Martinelli & Droit-Volet, 2022b) examined PoTJs under several contexts (i.e., task difficulty, emotional valence, stimulus duration). They once again examined differences in time perception, ranging from seconds (22, 33, and 44 seconds) to minutes (66, 99, and 132 seconds). They found that the passage of time depends on the most salient contextual information available. This contextual information might be related to task features, such as difficulty level. Alternatively, people might reflect on subjective cues present throughout the task (emotions). In other situations, it is the task's duration that provides the most

salient information about the pace of time. Therefore, the pace of time can depend on several characteristics in a single experiment (Droit-Volet et al., 2018). At present, my experiments have not provided evidence that the passage of time *directly* affects changes in duration estimation performance during long tasks. However, with increasing interest in this area of research, we are nonetheless closer to unravelling how these two forms of time judgement are interconnected.

An Expanded "Internal Clock"

To build on the extensive literature reviewed throughout this document and the results of the three experiments presented, I present a framework below to explain how duration estimates and PoTJs arise during prolonged tasks. This framework, depicted in Figure 20, is intended as a conceptual synthesis rather than a formal model, bringing together the many working parts of the cognitive theories discussed throughout this document and summarizing the potential interconnected mechanisms underlying our (often-distorted) sense of time.

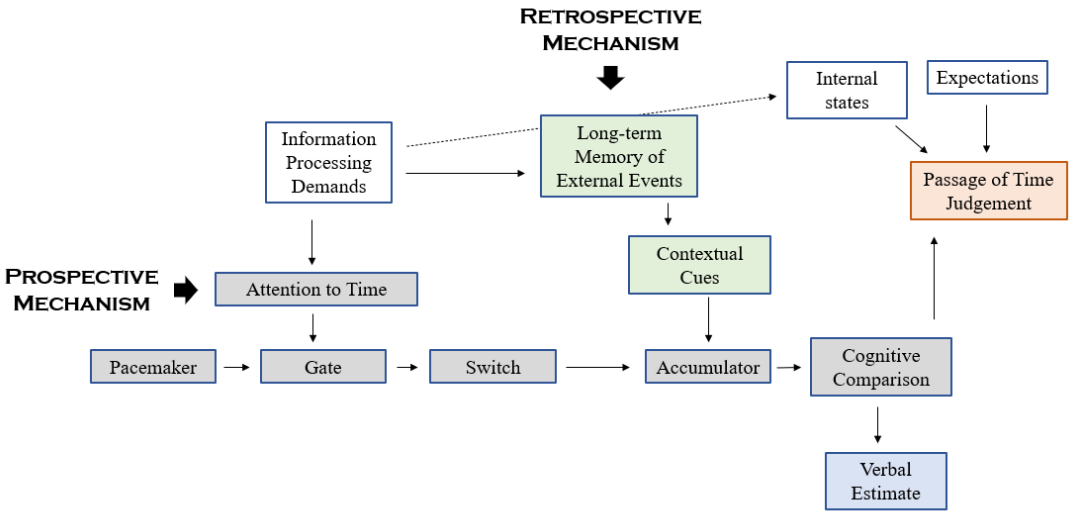


Figure 20. The Attentional-Gate Model (Grondin, 2025), adapted from Zakay and Block (1997), was combined with the contextual change hypothesis (Block & Reed, 1978) and mechanisms underlying PoTJs (Droit-Volet et al., 2018; Tanaka & Yotsumoto, 2017).

At its core, the framework assumes that time perception arises from the interaction between three primary sources of information: Attentional monitoring of time, memory for contextual changes, and internal states (e.g., boredom). In prospective paradigms, the accumulation of temporal information is mediated by attention (gate and switch; the AGM). Dividing attention between time and a concurrent task reduces this accumulation. In the retrospective paradigm, memory plays a crucial role in the accumulation of contextual cues to recall at the end of the interval. Both pathways lead to a cognitive comparison process, whereby our previous experiences determine the approximate duration of the interval.

Within this framework, duration estimates and PoTJs are related, but partially dissociable outcomes. Whereas duration estimates primarily reflect the accumulation and comparison of temporal information from attention and memory-based mechanisms, PoTJs instead are more directly derived from expectations and internal states like boredom and engagement, the latter of which themselves are influenced by the information processing demands of a task. However, given the use of a single task, it remains an open question whether this relationship holds across more complex or emotionally engaging real-world contexts. Nevertheless, the distinction between the two pathways may help explain why PoTJs do not always align with verbal duration estimates. The results of this thesis suggest that these mechanisms, although distinct, do not operate in isolation from each other. Rather, their relative contributions to time perception shift as the task duration increases.

In agreement with Droit-Volet et al. (2018), and as further evidenced by my second experiment, individuals may rely less on continuous attentional monitoring and more on memory and cues when judging time as the task duration increases. Interoceptive and affective states become more salient during prolonged tasks and play a role in shaping PoTJs. This shift may

explain why duration estimates become more accurate and why internal states like boredom and engagement are more strongly correlated with PoTJs in longer tasks compared to short ones, as was found in Experiment 2. Overall, this integrative "extended clock" model expands on existing models by emphasizing that time perception in prolonged tasks is not governed by a single mechanism. Rather, time perception is a dynamic experience arising from attentional, memory, and subjective processes that are weighted differently depending on the duration of a task.

While the framework described above is primarily descriptive, it generates clear avenues for future research. The model specifies three primary input streams (attention-related pulse accumulation, contextual change encoding, and interoceptive-affective states) and two output streams (duration estimates and PoTJs). Duration estimates and PoTJs can be conceptualized as formal weighted combinations of the three inputs. In short durations, attention is high while memory and interoception are low. At longer durations, memory and interoception increase in weight. Within this framework, future research could explicitly test dissociations between duration estimates and PoTJs by assigning formal weights to the input streams. Future research could also examine a role for uncertainty and metacognition within the model, and/or refine the indifference point even further in a well-controlled visual and memory search task to determine the point at which time perception is completely free of verbally expressed distortions.

Limitations

It is important to acknowledge that maximum control over the cognitive task, like the experiments presented in this thesis, has a significant limitation: daily life is rarely so controlled. I selected the visual and memory search task across all three experiments for two reasons. First, I aimed to recreate the conditions described in Walker et al. (2022) to compare the results of these experiments with past results. Second, the visual and memory search task allowed for maximum

control over the task's difficulty. The stimulus-response mapping procedure (consistent vs. varied mapping) is well-studied, and performance indices are well known (Cousineau and Larochelle, 2004; Hélie & Cousineau, 2011; Lefebvre et al., 2008; Moors & De Houwer, 2006). It was thus possible to conduct manipulation checks to assess whether participants remained attentive to the task throughout the experiments. Tobin et al. (2010), for instance, focused on ecological validity in their study by investigating how the experience of time differs while playing video games. This type of task features a mix of repetition, complexity, and novelty that is typical of daily life. In selecting a highly controllable task, I sacrificed this type of ecological validity. Instead, I favoured the ability to systematically test my hypotheses about psychological time distortions while holding the cognitive task constant.

Additionally, the impact of task difficulty on duration estimates at four minutes was curiously contradictory across Experiments 1 and 2. In the first experiment, estimates were unaffected by task difficulty. In the second experiment, there was a strong effect. Considering that task difficulty had no effect on time estimates in an eight-minute task using the same experimental manipulation (Walker et al., 2022), the effect of task difficulty may have been an anomaly in Experiment 2, which was then confirmed by a direct replication (Tandarich, 2026).

I had assumed that the stimulus-mapping procedure in the visual and memory search task would generate load effects at 30 seconds in Experiment 1. This prediction stemmed from Block et al. (2010), who found, in their meta-analysis, that active (as opposed to passive) processing, divided attention, and processing difficulty significantly impacted estimates of brief tasks. Similarly, Polti et al. (2018) found that increasing the number of items to be concurrently remembered in an N-back task shortened prospective estimates. Taken together, demands on working memory seem to impact timing performance. However, certain task features like long-

term memory activation, familiarity, and processing *changes*, or task switching, do not reliably impact estimates (Block et al. 2010; de Jong et al. 2025). Perhaps, our visual search task leveraged familiarity (consistent vs. varied targets) more than other cognitive resources. This resulted in clear performance differences in the task itself, but no consistent and replicable impact on timing performance. Future research could investigate whether the difficulty of the task affects estimates in the sub-second range to test whether this task shares any resources at all with temporal processing.

The experimental instructions may have also impacted the results of the three experiments. In keeping with Walker et al. (2022), a maximum of 90 minutes was communicated to participants in all three experiments. That is, the participants were told that the experiments would not last longer than 90 minutes. The choice to keep this anchor was once again to maintain as many similarities across experiments as possible. However, the 90-minute anchor could itself be a distorting factor. After all, Tanaka and Yotsumoto (2017) showed that PoTJs are influenced by the anchors provided, and duration estimates are distorted toward the anchors (König, 2005). Giving participants an explicit numerical value before beginning the task may thus skew the results. In other words, this could have created an *Anchoring bias* (Tversky and Kahneman, 1974). This bias may have contributed to the significant overestimation observed in short task conditions (e.g., estimates were close to two minutes in Experiment 1's retrospective 30-second condition). This perhaps resulted in a central tendency effect like Vierordt's law where the mid-point is used as a reference point biasing estimates toward that reference. This is typically seen in within-subject designs where a central tendency effect is observed over the course of repeating timing trials in an experiment (Murai & Yotsumoto, 2016). Future research could investigate the impact of varying anchors on duration estimates and PoTJs in a visual and memory search task.

If participants in brief (and consistently overestimated) tasks become more accurate with smaller anchors, it could help clarify the role of expectation in time perception, perhaps adding further nuance to the theory of prolonged time judgements discussed above.

Conclusion

The experiments in this document clearly demonstrate that the experience of time is multifaceted. We can perceive time as slowing down or speeding up while engaging in an activity, yet we sometimes provide contradictory estimates when asked to translate that experience into clock units. We know that we can feel time passing, describe its pace, assign a numerical value to that experience, and provide an index of our uncertainty about that value. Yet, the exact mechanism by which all this happens is only beginning to become clear.

Nevertheless, this thesis provides evidence supporting traditional models of time perception (e.g., the AGM) when examining estimation accuracy and uncertainty in prolonged tasks (e.g., four minutes). Specifically, when comparing dual-task (prospective) and single-task (retrospective) estimates, I observed the typical pattern in which time is overestimated to a greater degree when people intentionally encode it. Yet the role of task difficulty remains unclear, and thus so does the presumed boundary of attentional release.

Furthermore, this thesis found that estimates are fairly accurate around half an hour. Combined with the findings from other researchers in this area, a picture is beginning to emerge about the circumstances in which people are most accurate at estimating time. However, focusing only on the accuracy of an estimate will surely miss important information about people's internal temporal experiences.

Indeed, this thesis provides evidence that PoTJs and duration estimates share a similar mechanism (i.e., each varies with information-processing demands, though in different ways).

However, I did not find a compelling, consistent, direct relationship across experiments. That is, I did not find direct evidence for a compensatory mechanism in which people use the subjective pace of time to then over- or under-report it in clock units, though Experiment 3 provided avenues for future follow-up. Nevertheless, I replicated previous findings showing that participants consistently overestimate a brief cognitive task and that the pace of subjective time is influenced by factors that will inevitably be missed if duration estimate accuracy is the only measured outcome variable.

Together, these findings reinforce a central conclusion: psychological time is a product of the mind (Hughes & Trautmann, 1995; Zakay, 2014), meaning that our experience of time does not necessarily reflect objective duration. The extended clock model thus illustrates a novel integration of the AGM, the contextual change hypothesis, and mechanisms underlying PoTJs to illustrate distortions in the psychological experience of time during prolonged tasks. Psychological time is not governed by a single internal clock, but emerges from dynamic interactions among attention, memory, and subjective experience that shift systematically with task duration.

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Appendix A

ISPR System Notice

Study Name: Visual processing and memory experiment

Description: In this experiment, you will be asked to complete a Visual and Memory Search Task. You will be presented with a set of four alphanumeric characters (digits and/or letter) followed by a new set of four characters. It will be your job to press one key if you perceive that a character was present in both sets or to press a different key if you perceive that each set contained unique characters. This task will be repeated for a random number of trials. At the end of the experiment, you will be asked some basic demographic questions (age and gender) and will be asked for your feedback on the experiment. This is a computer task that can vary in the amount of time it takes to complete, however it will not exceed 90 minutes.

Eligibility Requirements: To participate in this study, you must be a student registered with the ISPR system. You must also have normal or corrected to normal vision.

Duration and Locale: The experiment will take a maximum of 90-minutes to complete and will take place in VNR3028C.

Compensation: You will receive 1.5% towards your course credit.

Researchers: Jesika Walker (Lead Researcher); and Dr. Denis Cousineau (Supervisor).

Your help with this project is greatly appreciated!

This study will only be conducted in English

Appendix B

Prospective Condition Consent Form

Title: Visual processing and memory experiment

I _____, choose to participate in an experiment about visual processing, memory, and time estimation.

This study aims to measure how you respond to digits and letters in a Visual and Memory Search task and how accurately you perceive the passage of time. The researcher for this study is **Jesika Walker** in the School of Psychology at the University of Ottawa. She is working under the supervision of **Dr. Denis Cousineau**.

Description of Study
In this experiment, you will be asked to complete a Visual and Memory Search Task. You will be presented with a set of four alphanumeric characters followed by a new set of four alphanumeric characters. It will be your job to press one key if you perceive that a character was present in both sets or to press a different key if you perceive that each set contained unique characters. This task will be repeated for a random number of trials. **At the end of the experiment, you will be asked to estimate the duration of the experiment.** You will also be asked some basic demographic questions (age and gender) and will be asked for your feedback on the experiment. This is a computer task that can vary in the amount of time it takes to complete, however the experiment will not exceed 90 minutes.

Duration of study and Compensation
The experiment can last up to 90 minutes but may end at any moment before 90 minutes is reached. Regardless of how long the experiment takes to complete, you will be compensated with 1.5% toward your course credit.

Risks and Discomfort
There are no potential physical or psychological risks associated with participation in this experiment.

Benefits
This research will help contribute to the development of our understanding on how the mind keeps track of time and fill current gaps in the time perception literature.

Anonymity
All data collected in this experiment will be kept strictly confidential through the assignment of a coded number. The information provided will be used for research purposes only and you will not be identified by name in any reports produced from this study.

Data Storage
Anonymous data will be kept indefinitely and stored on a password protected computer. Only

researchers involved in this study will have access to the data, however anonymous data may be made available to third parties for research purposes. Anonymized data may be used in future research, presentations, or future publications.

Right to withdraw
You have the right to withdraw your data at any time during the experiment or immediately after the experiment. You may do so for any reason and without academic penalty. Your participation in this study is completely voluntary. Should you choose to withdraw from the study, all information you have provided will be immediately destroyed. You will receive compensation for your participation in this study even if you choose to withdraw.

Study Results
If you would like a copy of the finished research project, you are invited to contact the researcher to request an electronic copy which will be provided to you.

CUREB contact information:

Should you have any ethical concerns with the study, or if you have any general questions about your rights as a research participant, please contact the Protocol Officer for Ethics in Research. For all other questions about the study, please contact the researchers.

Researcher contact information:

Jesika Walker
School of Psychology
University of Ottawa

Supervisor contact information:

Denis Cousineau
School of Psychology
University of Ottawa

_____ _____

Signature of participant Date

_____ _____

Signature of researcher Date

Appendix C

Retrospective Condition Consent Form

Title: Visual processing and memory experiment

I _____, choose to participate in an experiment about visual processing and memory.

This study aims to measure how you respond to digits and letters in a Visual and Memory Search task. The researcher for this study is **Jesika Walker** in the School of Psychology at the University of Ottawa. She is working under the supervision of **Dr. Denis Cousineau**.

Description of Study
In this experiment, you will be asked to complete a Visual and Memory Search Task. You will be presented with a set of four alphanumeric characters followed by a new set of four alphanumeric characters. It will be your job to press one key if you perceive that a character was present in both sets or to press a different key if you perceive that each set contained unique characters. This task will be repeated for a random number of trials. At the end of the experiment, you will be asked some basic demographic questions (age and gender) and will be asked for your feedback on the experiment. This is a computer task that can vary in the amount of time it takes to complete, however the experiment will not exceed 90 minutes.

Duration of study and Compensation
The experiment can last up to 90 minutes but may end at any moment before 90 minutes is reached. Regardless of how long the experiment takes to complete, you will be compensated with 1.5% toward your course credit.

Risks and Discomfort
There are no potential physical or psychological risks associated with participation in this experiment.

Benefits
This research will help contribute to the development of our understanding on visual processing and memory.

Anonymity
All data collected in this experiment will be kept strictly confidential through the assignment of a coded number. The information provided will be used for research purposes only and you will not be identified by name in any reports produced from this study.

Data Storage

Anonymous data will be kept indefinitely and stored on a password protected computer. Only researchers involved in this study will have access to the data, however anonymous data may be made available to third parties for research purposes. Anonymized data may be used in future research, presentations, or future publications.

Right to withdraw

You have the right to withdraw your data at any time during the experiment or immediately after the experiment. You may do so for any reason and without academic penalty. Your participation in this study is completely voluntary. Should you choose to withdraw from the study, all information you have provided will be immediately destroyed. You will receive compensation for your participation in this study even if you choose to withdraw.

Study Results

If you would like a copy of the finished research project, you are invited to contact the researcher to request an electronic copy which will be provided to you.

CUREB contact information:

Should you have any ethical concerns with the study, or if you have any general questions about your rights as a research participant, please contact the Protocol Officer for Ethics in Research. For all other questions about the study, please contact the researchers.

Researcher contact information:

Jesika Walker
School of Psychology
University of Ottawa

Supervisor contact information:

Denis Cousineau
School of Psychology
University of Ottawa

_____ _____

Signature of participant Date

_____ _____

Signature of researcher Date

Appendix D

Visual and Memory Search Instructions

(Programmed in E-prime; Psychology Software Tools, Pittsburgh, PA)

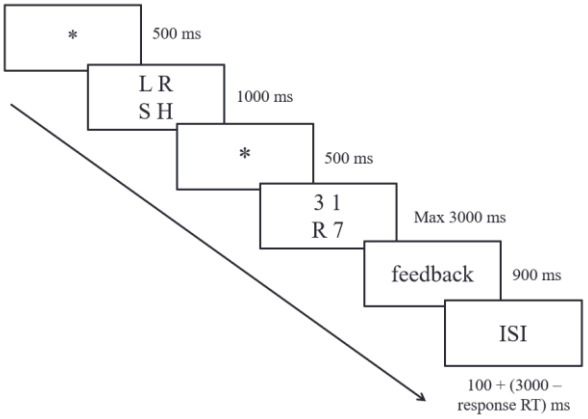
The following instructions were given to participants verbally before beginning the experiment and also provided on screen before they began the task.

"On each trial, you will see a set of four characters. These are your targets. Please memorize these characters. You will then see another set of four characters. Please decide as accurately as possible whether one of the targets you memorized is present in this new set. There is a short amount of time to respond, so please be quick in your decisions."

On screen instructions:

Here is an example of a typical trial.

The participant saw an example of a target-present trial on the computer screen that went as follows:



"In this example, the second set of digits did contain the target. The letter 'R' was present in both sets. You will first have 20 practice trials to familiarize with the task.

Please press the "z" key when you think the target is present. Please press the "m" key when you think the target is absent." (The keys were counter-balanced by participant number).

Press 'Enter' to start the practice trials"

The participant then performed 20 practice trials.

"Now that you've had some practice, you can begin the experiment. You will be given a random number of trials. Please try to remain over 90% accurate in your decisions. Press 'Enter' when you are ready to begin."

Appendix E

[Question displayed via Qualtrics, (Provo, UT) survey system]

Question 1:

How long was this task from the moment you pressed the 'Start' key to your last response? Your estimate should **not** include the practice trials completed prior to pressing the start key. Please be as accurate as possible down to the nearest minute and second. Please type your answer in the box below and press 'Enter' to submit a time estimate.

Located underneath this message, there was a small box for their response in minutes and seconds.

Question 2:

Please fill in the blanks using the computer keyboard. Please be as accurate as possible down to the nearest minute and second: At the very least, I think the task took me ____ minutes and ____seconds to complete. At very most, I think the task took me ____ minutes and ____seconds to complete. Press 'Enter' to submit your response."

Question 3:

How fast or slow did time seem to pass throughout the task?

1	2	3	4	5	6	7
(Very Slow)			(Neutral)			(Very Fast)

Demographic Information and Participant Feedback

Do you have normal or corrected to normal vision? Yes or No

Please indicate your age:____
Please indicate your gender: _____

Please indicate how engaged you were throughout the Visual and Memory Search Task:

1	2	3	4	5	6	7
(Not Very Engaged)			(Neutral)			(Very Engaged)

Please indicate how bored you were throughout the Visual and Memory Search Task:

1	2	3	4	5	6	7
(Very Bored)			(Neutral)			(Not Bored At all)

Appendix F

Secondary Consent Form

Researcher contact information:

Jesika Walker
School of Psychology
University of Ottawa

Supervisor contact information:

Dr. Denis Cousineau
School of Psychology
University of Ottawa

ISPR Title: Visual processing and memory experiment

Project Title: Prospective and Retrospective Time Estimation: Investigating the Effects of Task Duration and Cognitive Load

Informed Consent to the Use of Data:

The purpose of this informed consent is to ensure that you now understand the true purpose of the study and that you agree to allow your data to be used for research purposes. Because you were only told of the procedures and not the purpose of this study at the outset, we are now asking for your consent to allow your data to be used.

Purpose

The purpose of this study is to assess whether time estimates are more accurate in an easy, difficult, short, or long task, and whether these results depend on if you knew to pay attention to time throughout the experiment or not.

Anonymity/Confidentiality

All data collected in this experiment will be kept strictly confidential through the assignment of a coded number. The information provided will be used for research purposes only and you will not be identified by name in any reports produced from this study. Anonymized data may be used in future publications.

Right to withdraw data

You have the right to indicate that you do not wish your data to be used in this study. If you indicate this is your choice, then all measures you have provided will be destroyed. You will receive compensation for your participation in this study even if you choose to withdraw.

Signatures:

I have read the above description of the study investigating time estimation, task difficulty, and task duration. My signature indicates that I agree to allow the data I have provided to be used for these purposes.

Full Name (Print): _____

Participant Signature: _____

Date: _____

Researcher Signature: _____

Date: _____

Appendix G

Debriefing Form

Prospective and Retrospective Time Perception:
Investigating the Effects of Task Duration and Cognitive Load

What are we trying to learn in this research?

This study examines attention to time, task duration, and task difficulty on the accuracy of a time estimate. Although time estimates are typically made after completing a task, they differ in fundamental ways depending on whether or not participants explicitly attended to the passage of time throughout the task (Block & Zakay, 1997). However, it is unclear how a task's duration interacts with participants' attention to time because research in this area typically focuses on short tasks (under two minutes). As such, the purpose of this experiment is to investigate time estimates for short and long durations. Moreover, it has been found that the accuracy with which people can estimate the duration of a task depends on the task's difficulty (Block, Hancock, & Zakay, 2010). This experiment thus contained both an easy task condition and a difficult task condition to investigate this effect.

The task that you completed is called a Visual and Memory search task and it allowed us to manipulate how challenging the task is to perform. We will compare your time estimates with other groups, some of which performed the task at the same difficulty level as you and some did not. This way, we can examine whether time estimates are more accurate in an easy, difficult, short, or long task, and whether the results depend on if you knew to pay attention to time throughout the experiment or not.

What are our hypotheses and predictions?

We predict that when a task is easy, people who are aware of an impending time estimate throughout the task will provide longer estimates than people who were not aware (Block & Zakay, 1997).

We predict that when the task is difficult, people who are aware of the impending time estimate will provide shorter estimates compared to those who were unaware. This is the opposite of what is predicted to occur in the easy task condition (Block et al., 2010). However, this pattern will be especially true in the shortest condition when people have not had much practice on the task. Therefore, we expect an interaction to occur between task difficulty, task duration, and people's awareness of an impending time estimate.

Why is this important to scientists or the general public?

To regulate daily activities, people rely on an internal representation of time. People's ability to coordinate their activities in time is extremely complex, especially when engaged in a computer-based activity. Consequently, the relationship between time perception and task demands is an increasingly important area of interest (Block et al. 2010). However, the fundamental processes

underlying time estimation are not clearly understood. As such, this study will help clarify what type of conditions make it more or less likely for the average person to accurately estimate time. This will help contribute to, and refine, contemporary models of human time perception.

Where can I learn more?

To better understand how attention to time influences the accuracy of a time estimate, read Block and Zakay (1997). If you would like a review of direct comparisons between conditions in which people actively keep track of time or not, see Tobin et al. (2010). If you would like to learn more about how task difficulty interacts with attention to time, read Block et al. (2010). Finally, if you would like to learn more about how to manipulate task difficulty in a Visual and Memory Search Task, read Schneider and Shiffrin (1977).

Block, R. A., Hancock, P. A., & Zakay, D. (2010). How cognitive load affects duration judgments: A meta-analytic review. *Acta psychologica*, *134*(3), 330-343.

Block, R. A., & Zakay, D. (1997). Prospective and retrospective duration judgments: A meta-analytic review. *Psychonomic Bulletin & Review*, *4*(2), 184-197.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological review*, *84*(1), 1.

Tobin, S., Bisson, N., & Grondin, S. (2010). An ecological approach to prospective and retrospective timing of long durations: a study involving gamers. *PloS One*, *5*(2), e9271.

What if I have questions later?

If you have any questions concerning this research, please contact Jesika Walker or Dr. Denis Cousineau.

Should you have any ethical concerns with the study, or if you have any general questions about your rights as a research participant, please contact the Protocol Officer for Ethics in Research.

Thank you for participating in this research. Your time and effort are greatly appreciated!

Appendix H

Experiment 2 Components

Administrative

This experiment must be completed on a computer or tablet with a keyboard. Please do not use a cellphone or device without a physical keyboard.

○ I understand

Consent Form

Please save/print this form

REB Clearance # H-01-22-7728 Date of ethics clearance: 28/01/2022

This study aims to measure how you respond to digits and letters in a Visual and Memory Search task and how accurately you perceive the passage of time. The researcher for this study is Jesika Walker in the School of Psychology at the University of Ottawa. She is working under the supervision of Dr. Denis Cousineau.

In this experiment, you will be asked to complete a Visual and Memory Search Task. You will be presented with a set of four alphanumeric characters followed by a new set of four alphanumeric characters. It will be your job to press one key if you perceive that a character was present in both sets or to press a different key if you perceive that each set contained unique characters. This task will be repeated for a random number of trials. At the end of the experiment, you will be asked to estimate the duration of the experiment. You will also be asked about your experiences during the experiment and some basic demographic questions (age and gender).

This is a computer task that can vary in the amount of time it takes to complete. The experiment can last up to 90 minutes but may end at any moment before 90 minutes is reached. Regardless of how long the experiment takes to complete, you will be compensated with 1.5% toward your course credit.

Risks and Discomfort:

There are no potential physical or psychological risks associated with participation in this experiment.

Benefits:

This research will help contribute to the development of our understanding on how the mind keeps track of time and fill current gaps in the time perception literature.

Anonymity:

All data collected in this experiment will be kept strictly confidential through the assignment of a coded number. The information provided will be used for research purposes only and you will not be identified by name in any reports produced from this study. Data Storage Anonymous data will be kept indefinitely and stored on a password protected computer.

Only researchers involved in this study will have access to the data, however anonymous data may be made available to third parties for research purposes. Anonymized data may be used in future research, presentations, or future publications.

Right to withdraw:

You have the right to withdraw your data at any time during the experiment or immediately after the experiment. You may do so for any reason and without academic penalty. Your participation in this study is completely voluntary.

Should you choose to withdraw from the study, all information you have provided will be immediately destroyed. You will receive compensation for your participation in this study even if you choose to withdraw.

Study Results:

If you would like a copy of the finished research project, you are invited to contact the researcher to request an electronic copy which will be provided to you.

REB contact information: Should you have any ethical concerns with the study, or if you have any general questions about your rights as a research participant, please contact the Protocol Officer for Ethics in Research.

For all other questions about the study, please contact the researchers. Jesika Walker, Denis Cousineau, School of Psychology, University of Ottawa,

I have read this form and I choose to participate in an experiment about time estimation and perception.

○ Yes ○ No

ID block

Please enter your 6 digit code

Videos



Please watch this short video. It contains important instructions for the experiment. If sound doesn't work, use the automated youtube captions

How to remove the time from the task bar

Windows: Link

Mac: Link

Video #2

Please watch this second short video below for instructions on how to do the visual and memory search task.

If sound doesn't work, use the automated Youtube captions



Please make sure your computer is fully charged and/or plugged in

VisualSearchBlock

Experiment loading...

If you see this message more than 10 seconds, please contact Jesika Walker. Sorry for the inconvenience...

Survey

How long was the visual and memory search task? Please DO NOT include the practice trials you did before beginning the task.

How many minutes?

Plus, how many seconds?

Now we would like you to provide a range. What is the maximum and minimum amount of time you think you spent on the task? Your answer should NOT include the practice trials you did before the main task.

Please fill in the blanks to provide a range:

	Minutes	+ Seconds
I think the task took a MAXIMUM of	☐	☐
	Minutes	+ Seconds
I think the task took a MINIMUM of	☐	☐

Regardless of your previous answers, please indicate how fast or slow time FELT like it passed throughout the task

1 (very slow)	2	3	4 (neutral)	5	6	7 (very fast)
○	○	○	○	○	○	○

.

Now we want to know about your experience of the Visual and Memory Search Task.
Please be as honest as possible

	1 (not very)	2	3	4 (neutral)	5	6	7 (very)
Please indicate how **engaged** you were in the task	○	○	○	○	○	○	○
Please indicate how **bored** you were throughout the task	○	○	○	○	○	○	○
Please indicate how **focussed/attentive** you were throughout the task	○	○	○	○	○	○	○
Please indicate how **difficult/challenging** you found the task	○	○	○	○	○	○	○
Please indicate how **new** the task felt to you	○	○	○	○	○	○	○

	1 (not very)	2	3	4 (neutral)	5	6	7 (very)
Please indicate how **fun** the task was for you	○	○	○	○	○	○	○
How much do you agree with the statement "I have **never** used a computer"?	○	○	○	○	○	○	○
Please indicate how **skilled/capable** you felt during the task	○	○	○	○	○	○	○
How **distracting** was your environment during the task?	○	○	○	○	○	○	○

Did you check the time at all during this experiment?

Please be as honest as possible. You will not be penalized for saying yes.

○ Yes ○ No

Did you perform this experiment on a computer, laptop, or propped-up tablet with a keyboard?

○ Yes ○ No

If you answered "no" to the question above, please describe your setup:

How tired/fatigued were you during the task?

1 (not very)	2	3	4 (neutral)	5	6	7 (very)
○	○	○	○	○	○	○

Is there anything else that may have impacted your ability to perform in this experiment (e.g., extreme stress, pain, medication, cannabis use, alcohol use, diagnosed ADHD, etc.)?

If so, please describe in the box below. *Note that this question is optional.

Please indicate your age

Please indicate your gender

If you have any feedback that you would like to share with the researchers, please provide it below (this is optional).

In case you are wondering...

The visual and memory search task that you did (excluding practice) was _____ minutes long.

To restore the time on your task bar, click the following links:

Windows: Link

Mac: Link

Debriefing Form (please print this form)

What are we trying to learn in this research?

This study examines task duration and task difficulty on the accuracy of a time estimate. It also aims to explore how a person's feelings toward a task (such as enjoyment) might impact their perception of time. Research in this area typically focuses on short tasks (under two minutes). As such, the purpose of this experiment is to investigate time estimates for longer durations. Moreover, it has been found that the accuracy with which people can estimate the duration of a task depends on the task's difficulty (Block,

Hancock, & Zakay, 2010). This experiment thus contained both an easy task condition and a difficult task condition to investigate this effect. The task that you completed is called a Visual and Memory search task and it allowed us to manipulate how challenging the task is to perform. We will compare your time estimates with other groups, some of which performed the task at the same difficulty level as you and some did not. This way, we can examine whether time estimates are more accurate in an easy or difficult task and whether the duration of the task influences this result.

What are our hypotheses and predictions?

It is hypothesized that the length of the task will moderate how accurate people are at estimating the time. Specifically, overestimation will occur in the shorter condition, while underestimation will occur in the longer conditions. However, because of the repetitive nature of the visual and memory search task, people will report time as passing slowly. We also predict that people will report compensating for a variety of factors while formulating their duration estimate (e.g., task novelty, skill level, enjoyment, perceived difficulty).

Therefore, this experiment will highlight the role of internal experiences whereby the duration estimate is formulated based on an appraisal of the task qualities.

Why is this important to scientists or the general public?

To regulate daily activities, people rely on an internal representation of time. People's ability to coordinate their activities in time is extremely complex, especially when engaged in a computer-based activity. Consequently, the relationship between time perception and task demands is an increasingly important area of interest (Block et al. 2010). However, the

fundamental processes underlying time estimation are not clearly understood. As such, this study will help clarify what type of conditions make it more or less likely for the average person to accurately estimate time. This will help contribute to, and refine, contemporary models of human time perception.

Where can I learn more?

To better understand how attention to time influences the accuracy of a time estimate, read Block and Zakay (1997). If you would like a review of direct comparisons between conditions in which people actively keep track of time or not, see Tobin et al. (2010). If you would like to learn more about how task difficulty interacts with attention to time, read Block et al. (2010). Finally, if you would like to learn more about how to manipulate task difficulty in a Visual and Memory Search Task, read Schneider and Shiffrin (1977).

Block, R. A., Hancock, P. A., & Zakay, D. (2010). How cognitive load affects duration judgments: A meta-analytic review. Acta psychologica, 134(3), 330-343.

Block, R. A., & Zakay, D. (1997). Prospective and retrospective duration judgments: A meta- analytic review. Psychonomic Bulletin & Review, 4(2), 184-197.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. Psychological review, 84(1), 1.

Tobin, S., Bisson, N., & Grondin, S. (2010). An ecological approach to prospective and retrospective timing of long durations: a study involving gamers. PloS One, 5(2), e9271.

What if I have questions later?

If you have any questions concerning this research, please contact Jesika Walker or Dr. Denis Cousineau. Should you have any ethical concerns with the study, or if you have any general questions about your rights as a research participant, please contact the Protocol Officer for Ethics in Research.

Thank you for participating in this research. Your time and effort are greatly appreciated!

Appendix I

Variability of PoTJs, engagement, and boredom ratings from Walker (2019).

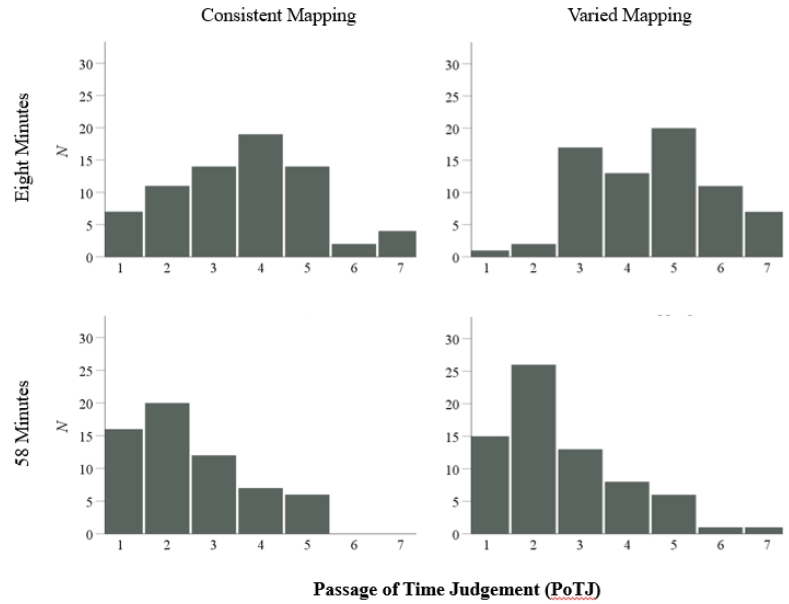


Figure I.1. PoTJ ratings on a 7-point Likert scale (1 = very slow, 7 = very fast) in Walker (2019). Results show variability of responses among participants across duration and cognitive load (varied vs. consistent mapping) conditions.

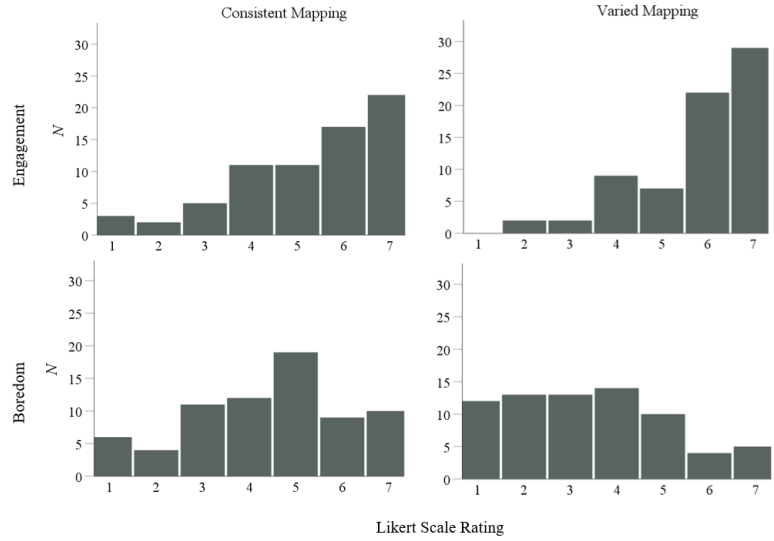


Figure I.2. Engagement and boredom ratings on a 7-point Likert scale (1 = not at all, 7 = very) of the eight-minute conditions (Walker, 2019). Results show variability of responses among participants (N = 71) in both consistent mapping and varied mapping versions of the Visual and Memory Search task.