VIRTUAL REALITY'S EFFECT ON PROSPECTIVE TIME ESTIMATION IS INCONSISTENT AND SENSITIVE TO ENVIRONMENT SIZE

by

Grayson Mullen

B.S., The University of California, Santa Cruz, 2020

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARTS

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Psychology)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

August 2023

The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the thesis entitled:

Virtual reality's effect on prospective time estimation is inconsistent and sensitive to environment size

submitted by Grayson Mullen in partial fulfilment of the requirements for

the degree of Master of Arts

in Psychology

Examining Committee:

Alan Kingstone, Professor and Distinguished University Scholar, Psychology, UBC
Supervisor

Daniela Palombo, Associate Professor, Psychology, UBC
Supervisory Committee Member

Lawrence Ward, Professor Emeritus, Psychology, UBC
Supervisory Committee Member

Abstract

Despite anecdotal reports that time flies in virtual reality (VR), evidence for this effect has been scarce. Only one prior study (Mullen and Davidenko, 2021) reported that people prospectively underestimated time in VR relative to a matched non-VR condition. Participants were instructed to play a video game either in VR or on a conventional monitor (CM) for 5 minutes without access to a clock. The VR group produced significantly longer intervals, suggesting that they underestimated time. The present study attempts to replicate this finding and identify factors within VR that might mediate its effect on time estimation.

VR was found to be associated with *over*estimation of time in Experiment 1 and had no significant effect on time estimation in Experiment 2, contrary to the VR-induced underestimation effect reported by Mullen and Davidenko (2021). VR appears not to have a general and reliable impact on time estimation.

However, the VR group in Experiment 2 produced significantly longer intervals than the VR group in Experiment 1, while there was no corresponding difference in CM intervals. This difference may be related to changes in virtual camera size, which inversely determines the apparent scale of the VR environment.

Experiment 3 tested this interpretation by assigning participants to perform an interval production task in a VR environment with a small, medium, or large virtual camera. Participants tended to underestimate time when the virtual environment appeared bigger (in smaller camera size conditions), and overestimate time when it appeared smaller (in larger camera size conditions). This points to a potential mechanism by which people may tend to underestimate time in more expansive VR environments, even though the effect has not been reliably observed

in controlled experiments. The kind of VR experience that can be easily matched for content with a non-VR display (that is, a confined environment that does not encourage 360° exploration) may not be the kind that can elicit a strong time underestimation effect.

Lay Summary

Virtual reality (VR) has been used to shorten chemotherapy patients' perceived duration of their treatments. Yet there is little evidence that VR is more effective at distorting time perception than other kinds of digital media.

Only one prior study reported evidence that people underestimate time prospectively (i.e., while actively keeping track of time) in VR compared to when viewing the same content on a non-VR display. In attempting to replicate that study, I found the effect was not reliable. VR appears not to have a consistent impact on time estimation.

However, I observed that participants underestimated time in larger VR environments and overestimated time in smaller ones. This aligns with previous work demonstrating that perception of time can be influenced by perception of space. Vast VR environments that encourage visual exploration across a wide field may be the most useful for inducing time underestimation effects.

Preface

I wrote the manuscript with valuable edits from Dr. Alan Kingstone. I designed all three experiments and developed the virtual environments used as stimuli. I was responsible for roughly half of participant testing; the other half was carried out by undergraduate research assistants Ethan Lee, Amina Abdelbary, Olivia Kajoba, and Fiona Sjaus. I conducted all data analysis, with the benefit of advice from Oliver Jacobs and Kevin Roberts. The study was approved by the University of British Columbia's Behavioral Research Ethics Board (Certificate Number: H10-00527).

Table of Contents

Abstract ..... **iii**

Lay Summary ..... **v**

Preface ..... **vi**

Table of Contents ..... **vii**

List of Tables ..... **x**

List of Figures ..... **xi**

Acknowledgements ..... **xii**

Chapter 1: Introduction **1**

1.1 Time Estimation 2

1.1.1 Retrospective Estimation 3

1.1.2 Prospective Estimation 4

1.2 Time Estimation in Virtual Reality 5

1.2.1 Mullen and Davidenko (2021) 6

Chapter 2: Experiment 1 ..... **8**

2.1 Methods 8

2.1.1 Participants 9

2.1.2 Stimulus 10

2.1.3 Apparatus 11

2.1.4 Questionnaire 12

2.1.5 Procedure 12

2.2 Results 13

2.2.1 Questionnaire Results 15
2.3 Discussion 16
Chapter 3: Experiment 2 19
3.1 Methods 19
3.1.1 Participants 19
3.1.2 Stimulus 20
3.1.3 Apparatus 20
3.1.4 Questionnaire 21
3.1.5 Procedure 21
3.2 Results 22
3.2.1 Comparing Experiment 1 with Experiment 2 23
3.2.2 Questionnaire Results 25
3.3 Discussion 26
Chapter 4: Experiment 3 30
4.1 Methods 30
4.1.1 Participants 30
4.1.2 Stimulus 31
4.1.3 Apparatus 32
4.1.4 Questionnaire 32
4.1.5 Procedure 32
4.2 Results 33
4.2.1 Questionnaire Results 34
4.3 Discussion 35

Chapter 5: Conclusion **39**

5.1 Summary 39

5.2 General Discussion 39

5.3 Limitations and Future Work 41

References **44**

Appendices **51**

Appendix A Experiment 1 Questionnaire 51

A.1 Bodily awareness (adapted from Murray and Gordon, 2001) 51

A.2 Presence (adapted from Slater and Steed, 2000) 53

A.3 Flow state experience (adapted from Magyaródi et al., 2013) 54

A.4 Single-item questions 55

Appendix B Experiment 2 Questionnaire 56

B.1 Single-item questions from Mullen and Davidenko (2021) 56

B.2 Immersion scale from Mullen and Davidenko (2021) 56

B.3 New questions 58

Appendix C Experiment 3 Questionnaire 60

C.1 Presence (adapted from Slater and Steed, 2000) 60

C.2 Single-item questions 60

List of Tables

Table 4.1.2 Apparent dimensions in each of the three camera size conditions in Experiment 3 . 31

List of Figures

Figure 2.1.2 A level of the maze game from the 10-minute conventional monitor condition..... 10

Figure 2.2 Experiment 1 produced interval durations by display type and instructed duration ... 13

Figure 3.2 Experiment 2 produced interval durations by display type 22

Figure 3.2.1 Produced interval durations in 5-minute conditions, Experiments 1 and 2..... 24

Figure 4.2 Experiment 3 produced interval durations by virtual camera size 33

Acknowledgements

I am grateful to my supervisor, Dr. Alan Kingstone, for his incisive feedback and his confidence in this work. I am also very fortunate to benefit from the expert perspectives of my other committee members, Dr. Daniela Palombo and Dr. Lawrence Ward.

I deeply appreciate my lab mates in the Brain, Attention, and Reality Lab for their patience and generosity in answering my questions when I interrupt them at the desks.

Lastly, I would like to thank my research assistants Ethan Lee, Amina Abdelbary, Olivia Kajoba, and Fiona Sjaus for the many hours they spent collecting data for these experiments.

Chapter 1: Introduction

Virtual reality developers have suggested that "time passes differently" in VR: that someone can spend an hour inside it and feel that only 15 minutes have passed (Miller, 2016). Yet the few experiments that have tested VR's impact on time estimation have found mixed results. It has not been clearly established that VR affects time estimation, and (if it does) what aspects of VR might be instrumental in the effect.

If people do underestimate the time they spend in VR, it may pose a problem for recreational users. Wood et al. (2007) found that time loss was experienced by 99% of surveyed participants who played video games, 67.5% of whom reported that the effect was sometimes or always "a bad thing." Although time loss can be a component of non-problematic engagement, it has also been associated with disordered gaming (Nuyens et al., 2019). Spending excessive amounts of time playing video games can interfere with academic and job performance, sleep quality, and psychosocial well-being (Griffiths et al., 2012). It is not yet clear whether VR games exacerbate time loss compared to conventional video games.

In some contexts, an underestimation effect has valuable utility. Distraction therapy can reduce pain and anxiety during unpleasant medical treatments (Miller et al., 1992), and its effectiveness is potentially related to the distractor's ability to make patients underestimate time during treatment (Schneider et al., 2011; Loreto-Quijada et al., 2014). VR has been found to induce time underestimation in chemotherapy patients when compared to music therapy (Schneider et al., 2011) or no task (Chirico et al., 2016). However, the VR experiences used in these studies were not compared with non-VR media displaying matched content. This leaves open the possibility that the reported effects could be elicited by interactive digital media in

general. More controlled experiments are required to investigate the specific contribution of VR to the success of these interventions.

Isolating an effect of VR on time estimation will help clarify its value for distraction therapy, as well as its potential to cause undesired time loss. It will also form a basis for teasing apart basic factors that might mediate the effect. Once identified, these factors could be manipulated to strategically magnify or mitigate VR's effect on time estimation in applied settings.

An effect of VR on time estimation also has implications for our understanding of how cognition may be fundamentally altered by VR. Time estimation is a high-level process that involves a complicated integration of perception, attention, and memory (Matthews and Meck, 2016), and a distortion in time estimation typically reflects a manipulation of one or more of these component functions. Identifying an effect of VR on time estimation, as well as the conditions necessary for it to occur, can support further research into how VR affects underlying cognitive processes.

1.1 Time Estimation

There are several facets of time perception, and each is sensitive to different factors. We can explicitly estimate the duration of an interval (Block and Zakay, 1997), we can judge the speed of time (Sucala et al., 2011), and we can report the extent to which we feel that time is available to us (Rudd et al., 2012). The present study focuses on duration judgments.

Most experiments on time perception measure duration judgments, and the cognitive processes that underlie them are better understood than more subjective or attitudinal types of time perception. Duration judgments also have more direct consequences for planning, as a

distortion in the perceived speed or availability of time does not necessarily impair planning beyond the extent to which it impairs duration judgment. For example, a feeling that time is moving fast or slow will not cause someone to miss an appointment unless it is accompanied by an underestimation of time leading up to the appointment. Duration judgments may therefore have more bearing on time loss and its practical consequences.

Although language related to slowing and speeding is often used to describe distortions in time estimation, judgments of the speed of time do not always align with duration estimates (Droit-Volet and Wearden, 2016). Some factors that reliably distort time estimation have no impact on passage of time judgments, and vice versa. Whether VR causes time to feel fast or slow is outside the scope of this study; my focus is on whether people tend to under- or overestimate the time they spend in VR.

1.1.1 Retrospective Estimation

Retrospective estimates are generated only after the judged interval has ended. If a participant's only initial instructions are to watch a film, for example, they generally will not allocate attentional resources to keep track of time. So if after the film ends the participant is asked to retrospectively estimate its duration, their estimate will be largely based on what they can recall about the film from memory.

Accordingly, factors that have been found to manipulate retrospective time estimation are mostly related to memory. Intervals tend to be retrospectively estimated as longer when more complex information can be recalled from it (Ornstein, 1969) and when that information is divided by many contextual changes over time (Block et al., 2010).

These estimates can be reported verbally (as a number of seconds or minutes), or by interval reproduction. In an interval reproduction task, the participant produces a new interval (e.g., by pressing a button to signal its beginning and end) that they think matches the duration of the interval they are judging. In comparison with verbal estimation, interval reproduction is less susceptible to rounding biases but also less feasible for long durations (Block et al., 2018).

1.1.2 Prospective Estimation

When participants know during the interval that they are expected to judge its duration, they estimate time prospectively. For example, an experimenter may tell participants before they watch a film that they will be asked to estimate its duration at the end.

A verbal estimate or interval reproduction task may be recorded for prospective methods, as with retrospective methods, but informing participants of the estimation task allows for more measurement options. In interval comparison tasks, for example, participants are asked to judge whether an interval is longer or shorter than a reference interval, or which of multiple reference intervals is closest in duration to the judged interval. In an interval production task, participants are instructed to report when they feel that a specified length of time has elapsed. This minimizes the risk of rounding bias entailed by verbal estimation and is less time-consuming than interval reproduction or comparison because no reference interval is presented.

Prospective time estimation is less sensitive to memory-related factors (like recalled contextual changes) and more sensitive to attentional load and arousal (Block and Zakay, 1997). We tend to underestimate time during tasks that are highly demanding of attention, and overestimate time while our attention is not captured. For example, an engrossing two-hour film

may be perceived as lasting only 90 minutes, while 10 minutes spent waiting in line may feel like 15. According to the attentional-gate model (Zakay and Block, 1996), this is because of an attentional resource trade-off between prospective time estimation and any nontemporal tasks. The model describes a kind of pacemaker that emits “pulses” at an arousal-dependent rate, and an attentional gate that limits the accumulation of pulses. When demanding tasks draw attention away from the passage of time, the estimator fails to notice more pulses—or ticks of their internal clock—causing subjective time to lag behind objective time.

However, not all attentionally demanding tasks interfere with time estimation. It has been noted that prospective time estimation is most impacted by concurrent tasks that use central executive control processes (Block et al., 2010), suggesting that executive control is implicated in a way that the attentional-gate model does not account for (Matthews and Meck, 2016). The attentional-gate model and its various successors are abstract; none succeeds at accounting for every factor that influences prospective time estimation. Still, prospective estimation is broadly distinguished from retrospective estimation by its sensitivity to attentional load.

Because VR more directly impacts attentional processes than memory processes, it seems theoretically more likely to interfere with prospective estimation than retrospective estimation.

1.2 Time Estimation in Virtual Reality

Few studies have compared time estimation between matched VR and non-VR conditions, and most of them have used small samples. Lugrin et al. (2019) found that VR was associated with retrospective underestimation when the virtual environment did not include an avatar, but Unruh (2021) found no effect using comparable methods with a larger sample.

Similarly, Rutrecht et al. (2021) found no effect of VR on retrospective estimates, time awareness, or subjective passage of time judgments.

The effect of VR on prospective estimation has been investigated by Schatzschneider (2016), van der Ham (2019), and Bruder and Steinicke (2014), all of whom found no significant difference between matched VR and non-VR conditions. These three studies used within-subjects designs that asked participants to produce verbal estimates of interval durations.

In summary, the bulk of published research on this subject suggests that VR does not produce a reliable effect on time estimation. The only reported significant effect on retrospective estimation was not replicated in a later study, and only one study (Mullen and Davidenko, 2021) has reported a significant effect on prospective estimation.

1.2.1 Mullen and Davidenko (2021)

Noting that every prior experiment testing the effect of VR on prospective estimation had recorded verbal estimates, Mullen and Davidenko (2021) used an interval production task instead. Verbal estimates are often rounded to the nearest minute. For example, a real interval of 5 minutes and 38 seconds is more likely to be verbally estimated as having lasted 5 or 6 minutes than any number in between. Interval production methods avoid this rounding bias by measuring actual durations that participants produce—these can be recorded with high precision and do not require the participant to explicitly generate a number.

Each participant in Mullen and Davidenko's (2021) experiment played a game both in VR and on a conventional monitor (CM) in a counterbalanced order, but there was such a strong anchoring effect between trials that opposite display effects were observed between participants' first and second trials. Among first trials, intervals produced in VR were significantly longer than

CM intervals, but among second trials VR intervals were significantly shorter. This led the authors to discard all second-trial data and recommend that future experiments use between-subjects designs.

Participants in the VR condition played for an average of 72.6 seconds longer before reporting that they felt 5 minutes had passed. This was the first experiment to find evidence that people prospectively underestimate time in VR relative to a matched non-VR condition. It is possible that this study was the first to report such an effect because the interval production task is more sensitive than the verbal estimation methods used in previous studies. Testing a between-subjects comparison was also crucial: if order effects were not accounted for in the analysis, the main effect of display type would not have been significant.

However, it is also possible that this was a spurious result—data collection was cut off at 39 participants by the onset of the COVID-19 pandemic. While past studies investigating the effect of VR on prospective time estimation have used similarly small samples (the largest of the three listed earlier was 29 participants), large samples are crucial when working with data prone to a low signal-to-noise ratio. Time estimates tend to be highly variable in any case, and this may be exacerbated when making between-subjects comparisons. To test the reliability of the finding that VR causes people to underestimate time, it is necessary to replicate Mullen and Davidenko's (2021) methods with a larger sample.

Chapter 2: Experiment 1

The aim of this experiment was to replicate Mullen and Davidenko's (2021) finding that participants underestimate time while playing a VR game compared to while playing a non-VR counterpart. I repeated the same between-subjects comparison of an interval production task in VR and conventional monitor (CM) conditions with changes to the design, stimuli, and post-task questionnaire.

Because of the order effects that led Mullen and Davidenko (2021) to only analyze each participant's first trial, participants in this experiment were assigned to produce only one interval. This obviates the need for two unique sets of mazes for the game, so all participants in this experiment play through the same maze set. To investigate the effect at a longer timescale, participants were assigned to produce an interval of either 5 or 10 minutes. I also matched the retinal size of the mazes between VR and CM versions (in the previous study they appeared larger in VR) to match the two display conditions more closely.

I hypothesized that participants would produce longer intervals in VR than on the conventional monitor, as was observed in the previous study. Self-report scales of bodily awareness, presence, and flow state experience were administered after the interval production task to investigate potential mediating factors of any effect of display type on time estimation.

2.1 Methods

2.1.1 Participants

According to power analysis, a minimum sample of 67 participants was required to reach 80% power to detect an effect as large as the one reported by Mullen and Davidenko (2021) (d = 0.69/f = 0.35). Data were collected from 113 undergraduate psychology students at the University of British Columbia who received course credit for their participation.

Mullen and Davidenko (2021) used three standard deviations above or below the mean as their outlier exclusion criterion, but that rule would have been unreasonably inclusive for this study's data. For example, the range of included durations for participants instructed to produce a 300-second interval in VR would have been -121 seconds to 634 seconds according to the standard deviation rule. I therefore used an interquartile range (IQR) method (Yang et al., 2019) instead, excluding durations further than 1.5*IQR above Q3 or below Q1 in each condition. For the same group instructed to produce 300-second intervals in VR, this included durations between 55 and 425 seconds.

I excluded data from six participants due to procedural errors, and two who produced outlier data according to the IQR rule. This left the final analysis with 105 participants (73.3% women, M_{age} = 20.7, SD = 2.6).

2.1.2 Stimulus

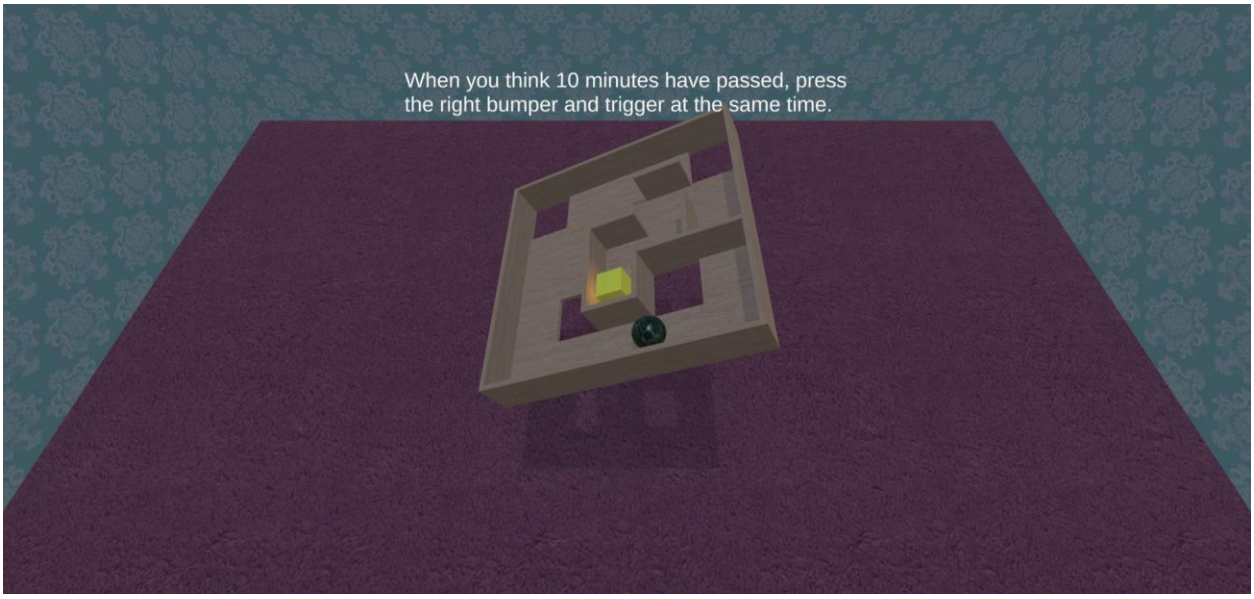

Figure 2.1.2 A level of the maze game from the 10-minute conventional monitor condition.

Four variations of the video game designed by Mullen and Davidenko (2021) were used. They differed in display type (VR or CM) and the durations that they instructed participants to produce (5 or 10 minutes) but were otherwise identical.

Each level of the game presents a floating maze that contains a loose marble and a fixed yellow cube representing a goal. Players use a gamepad to tilt the maze, which causes the marble to roll toward the maze's lowest side. The marble must be navigated around walls and gaps in the floor to reach the goal at the end of each maze. If the marble falls through a hole or is thrown over the outer walls of the maze, the current level restarts. If the marble reaches the goal, the next level begins. There are a total of 30 non-practice levels ordered by maze size (from smallest to largest) so that the game becomes progressively challenging over time.

Above the maze, white text fades in and out on a pseudorandomized 6-10 second cycle to remind participants of their task. During the practice level it reads, "When you're done

practicing, press the right bumper and trigger to start" and during the interval production task it reads, "When you think [5/10] minutes have passed, press the right bumper and trigger at the same time."

The virtual camera rig in VR versions of the game is scaled so that the retinal size of each maze is approximately matched between display conditions. Retinal size depended on each participant's posture and how they positioned their seat, but from a typical distance the practice level maze subtended a 22° x 22° visual angle in both VR and CM conditions.

2.1.3 Apparatus

Participants used a Logitech F710 Wireless Gamepad to control the game. The left joystick was used to tilt the maze in any direction, and holding down any of the colored buttons on the right face of the controller (A, B, X, or Y) would tilt the maze back to its flat starting position. Pressing the right bumper and trigger simultaneously would end the practice level (signaling the beginning of their interval production) and later end the game (signaling the end of the interval).

In conventional monitor conditions, the game was displayed on a Gigabyte G27Q monitor, which has a diagonal length of 27 inches and a resolution of 2560 x 1440p. Its refresh rate was set to 60Hz.

In virtual reality conditions, the game was displayed on a Meta Quest 2, which has a resolution of 1832 x 1920p per eye and was set to a refresh rate of 72Hz.

2.1.4 Questionnaire

All participants filled out an online questionnaire immediately after the interval production task. It included self-report measures of bodily awareness (adapted from Murray and Gordon, 2001), presence (adapted from Slater and Steed, 2000), and flow state experience (adapted from Magyaródi et al., 2013). It also asked individual questions about the participant's experience of the game and their level of prior experience with video games and VR. A complete list of questionnaire items is included in Appendix A.

2.1.5 Procedure

Participants filled out a COVID-19 contact tracing form, a demographics form asking their age and gender, and signed a consent form before beginning the experiment. They were also asked to keep cell phones and watches silenced and out of sight during the experiment. Each participant was assigned to one of two display types (virtual reality or conventional monitor) and one of two instructed interval durations (five or ten minutes) in a counterbalanced order. All participants across conditions sat at the same desk in the same testing room. To minimize environmental cues to time passing, the room's only window was covered completely, and the door was kept shut during the interval production task.

While the research assistant described the task and controls, participants began with a practice level. They were instructed to practice for as long as they wanted, but to try to play the subsequent timed part of the game for 5 or 10 minutes (depending on their group assignment) without looking at any kind of clock. Research assistants left the room before participants began the timed levels to avoid distraction during the interval production task.

After ending the interval production task, participants answered the post-task questionnaire.

2.2 Results

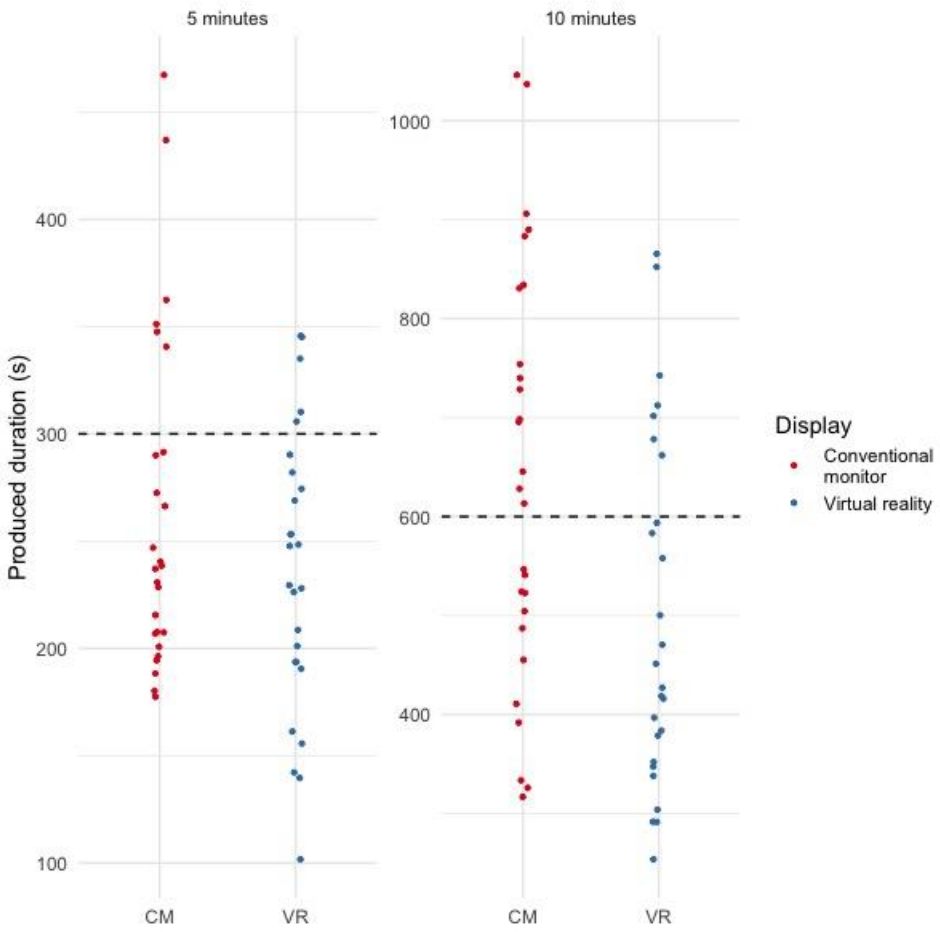

Figure 2.2 Experiment 1 produced interval durations by display type and instructed duration. The dashed lines represent the duration that participants were instructed to produce (5 or 10 minutes). Horizontal jitter was added to the dots for clarity.

Levene's test showed that the four groups' interval durations did not show homogeneity of variance ($F(3, 101) = 12.62$, $p < .001$). I therefore log-transformed the interval duration data,

and the transformed data met the homogeneity of variance assumption ($F(3, 101) = 1.13$, $p = .34$). I then ran a two-way ANOVA on the log-transformed data to test the effects of display type (VR or CM) and instructed duration (5 or 10 minutes) on produced interval duration. The results indicated a significant main effect of display type ($F(1, 101) = 8.48$, $p = .0044$, $\eta^2_G = .077$). Contrary to my hypothesis and the findings of Mullen and Davidenko (2021), participants produced significantly shorter intervals in VR than in CM conditions, suggesting that VR caused participants to prospectively *over*estimate time (to believe they spent more time in VR than they actually did). There was no significant interaction between display type and instructed duration ($F(1, 101) = 1.29$, $p = .26$, $\eta^2_G = .013$).

There was also a main effect of display type on practice time, such that participants in the CM conditions spent more time on the practice level than those in VR conditions ($F(1, 101) = 5.41$, $p = .022$, $\eta^2_G = .05$). Practice time was not significantly affected by instructed duration ($F(1, 101) = 0.18$, $p > .5$, $\eta^2_G = .0018$).

To test for an effect of display type on game performance, I measured the relationship between produced interval duration and the number of levels reached within each of the two display groups. For each group I ran 10,000 bootstrap samples to obtain a best-fit line describing the rate at which participants progressed through levels. Because the game starts on level 1 at 0 seconds, the y-intercept was fixed at 1. The slope of the line for each group is an estimate of how much of a level participants progressed through each second.

The 95% confidence interval around the slope for VR participants [0.015, 0.023] almost entirely overlapped with the confidence interval of the CM group [0.016, 0.022]. This suggests that participants progressed through levels at a similar rate across display conditions, so the

observed effect of VR on time estimates cannot be explained by differences in game performance.

2.2.1 Questionnaire Results

The difficulty of the game was not rated as significantly different between display groups ($F(1, 101) = 0.51$, $p = .48$, $\eta^2_G = 0.0050$). This aligns with the finding that participants progressed through levels at a similar rate in VR and CM conditions.

Bodily awareness was not rated as significantly different between display types ($F(1, 101) = 0.051$, $p > .5$, $\eta^2_G < .001$) or between instructed duration conditions ($p = .27$, $\eta^2_G = .012$). There was also no interaction between the two factors ($p > .5$, $\eta^2_G = .0023$).

Presence was not rated as significantly different between display types ($F(1, 101) = 0.46$, $p = .50$, $\eta^2_G = .004$) or between instructed duration conditions ($p = .26$, $\eta^2_G = .013$). There was also no interaction between the two factors ($p = .097$, $\eta^2_G = .027$).

Flow state experience was not rated as significantly different between display types ($F(1, 101) = 3.94$, $p = .050$, $\eta^2_G = .038$) or between instructed duration conditions ($p > .5$, $\eta^2_G = .0013$). There was also no interaction between the two factors ($p > .5$, $\eta^2_G < .001$).

Among participants who were instructed to play for five minutes, produced interval durations were not significantly correlated with bodily awareness ($r(50) = -.087$, $p > .5$), presence ($r(50) = .0058$, $p > .5$), or flow state experience ($r(50) = -.067$, $p > .5$). Produced interval durations in 10-minute conditions were likewise not significantly correlated with bodily awareness ($r(51) = .24$, $p = .082$), presence ($r(51) = .015$, $p > .5$), or flow state experience ($r(51) = .051$, $p > .5$).

2.3 Discussion

The results indicated that participants overestimated time in VR—an opposite effect from the finding that I sought to replicate. This surprising discrepancy may be accounted for by the present experiment's larger sample, discomfort with using shared VR headsets during the COVID-19 pandemic, and differences in materials.

Experiment 1 obtained a larger sample at 105 participants—data collection for Mullen and Davidenko's (2021) study was cut off at 39 included participants by the onset of the COVID-19 pandemic. This smaller sample means that the prior study carries a significantly larger risk of reporting a spurious result than the current experiment (Ioannidis, 2005).

The pandemic may have also changed the way participants interact with VR in ways that led them to produce shorter intervals. If participants were worried about virus exposure while wearing a headset that others have worn, anxiety may have caused them to overestimate time (Bar-Haim et al., 2009) or they may simply have wanted to end the experience sooner (Hornik, 1992). Although I do not expect other significant differences between the two populations (psychology undergraduate students at a Californian university in 2020 vs. those at a Canadian university in 2022) to have impacted the results, it is possible that populations with different levels of prior VR experience would show different effects of VR on time estimation, as people tend to overestimate time when exposed to novel stimuli (Tse et al., 2004). A post-task questionnaire in Experiment 2 addresses these possibilities.

There were also methodological differences between Mullen and Davidenko (2021)'s study and Experiment 1. For the present experiment I enlarged the virtual camera in VR to match the retinal size of each maze between conditions, collapsed two separate sets of mazes originally created for a within-subjects design into one longer set (allowing me to test participants at the

10-minute level), and used higher-resolution VR and CM displays. The potential consequences of these changes are explored in Experiments 2 and 3.

Participants were found to spend more time practicing the game in the CM conditions, but this finding should be taken with a grain of salt. As practice time was not one of my main variables of interest, the experimental protocol allowed for a lot of variation in the content and duration of the practice intervals. Some participants chose to start practicing the game during instructions, while others waited until the researcher finished speaking before using the controller at all—the clock started running when the researcher opened the practice level either way. Participants who had more questions, or who adjusted their seat or headset, could produce much longer practice level durations regardless of how much time they spent actively practicing. This comparison is revisited in Experiment 2.

My finding of no differences between display types in questionnaire responses suggests that VR did not significantly impact bodily awareness, presence, or flow state experience. While it has been previously observed that VR can reduce bodily awareness (Murray and Gordon, 2004), the effect seems to depend on characteristics of the virtual environment, and the necessary conditions for the reduction to occur have not been identified. The environment I used was relatively simple, unrealistic, and untraversable (participants were able to lean and scoot their chair, but not move in any other way through the real or virtual environment). A more naturalistic or immersive environment may be required for VR to reduce bodily awareness. Rutrecht et al. (2021) similarly found no difference in bodily awareness or flow between matched VR and non-VR conditions, although they did report significantly higher presence ratings in their VR condition.

It has been argued that comparing presence ratings between desktop (CM) and immersive (VR) virtual environments is problematic (Usoh et al., 2000) or that it is inappropriate to measure presence in desktop environments at all (Slater, 2009). Questions probing a participant's sense of "being there" may be interpreted differently depending on whether the judged environment is a real-world place, a VR environment, or a virtual environment displayed on a desktop monitor, because each type of environment affords fundamentally more or less realistic modes of interaction. Experiment 1's finding that presence was not rated differently in VR supports the notion that presence questionnaires may not be reliable for measuring differences between VR and non-VR display types.

Although flow states are thought to be characterized by distortions in time perception, I observed no relationship between self-reported flow ratings and produced interval durations. The purported "time has passed faster than normal" aspect of flow (Nakamura and Csikszentmihalyi, 2014) is likely more related to subjective passage of time judgments than to duration judgments (Droit-Volet and Wearden, 2016).

Chapter 3: Experiment 2

Experiment 2 replicates Mullen and Davidenko's (2021) methods as closely as possible to test whether the opposite findings of Mullen and Davidenko (2021) and Experiment 1 can be attributed to differences in experimental design. Most notably, the VR environment used in Experiment 1 appeared smaller than its counterpart in Mullen and Davidenko (2021).

If reverting to Mullen and Davidenko's (2021) methods reproduces the VR-induced underestimation effect that they reported, then changes to the stimuli or task likely elicited the overestimation effect reported in Experiment 1. If instead this experiment's results are consistent with Experiment 1 (if participants overestimate time in VR), then the divergence from Mullen and Davidenko (2021) may be attributed to non-methodological factors such as population characteristics (e.g., prior experience with VR, COVID-19 related discomfort).

3.1 Methods

3.1.1 Participants

Data were collected from 201 undergraduate psychology students at the University of British Columbia who received course credit for their participation. I excluded data from 9 participants due to procedural errors, and six who produced extreme outlier data (according to the IQR rule). This left the final analysis with 186 participants (76.9% women, M_{age} = 20.7, SD = 4.4).

3.1.2 Stimulus

I used the exact versions of the maze game that were used by Mullen and Davidenko (2021). These differ from the game used in Experiment 1 in the following ways:

- The retinal size of the maze is **not** matched between display conditions. Because the VR display covers a much wider field of view than the conventional monitor, the maze subtends a larger visual angle in VR conditions compared to CM conditions by default. For example, the practice maze viewed from a typical distance subtends a roughly 30° x 30° visual angle in VR and a 22° x 22° visual angle in the CM conditions.
- All four conditions instruct participants to produce a 5-minute interval.
- There are fewer levels of mazes (14 instead of 30) per condition. The levels are ordered by maze size, with the final level's maze being 2.5 times larger than the first level's maze in all versions of the game. This means that the increase in maze size between consecutive levels is roughly doubled when 14 levels are used instead of 30.
- Participants are assigned to play through one of two sets of mazes (A or B). The sets were designed to be balanced in size and difficulty; they were only separated to minimize familiarity effects in a within-subjects comparison that was initially planned by Mullen and Davidenko (2021).
- The opacity of the task reminder is set to fade in and out every 8 seconds consistently instead of on a pseudorandomized 6-10 second cycle.

3.1.3 Apparatus

Participants used a wired Xbox 360 controller to manipulate the maze. The control scheme was identical to the one used in Experiment 1.

In conventional monitor conditions, the game was displayed on a Dell ST2320L monitor, which has a diagonal length of 23 inches, a resolution of 1920 x 1080p, and a refresh rate of 60 Hz. In virtual reality conditions, the game was displayed on an Oculus Rift CV1, which has a resolution of 1080 x 1200p per eye and a refresh rate of 90Hz.

The VR headset and controller are identical to those used by Mullen and Davidenko (2021), and the conventional monitor is comparable.

3.1.4 Questionnaire

The first part of the post-task questionnaire is identical to the one used by Mullen and Davidenko (2021). This included questions about the participant's prior experience with VR and video games, subjective aspects of their experience during the interval production task, and a 19-item immersion scale. For the second part I appended new questions about COVID-19 concerns, mask-wearing, lens fogging in VR, and perception of the size of the virtual environment. A complete list of all questionnaire items used in Experiment 2 is listed in Appendix B.

3.1.5 Procedure

Participants were assigned to produce a 5-minute interval in one of two display conditions (VR or CM) with one of two maze sets (A or B) in a counterbalanced order. The procedure was otherwise identical to Experiment 1.

3.2 Results

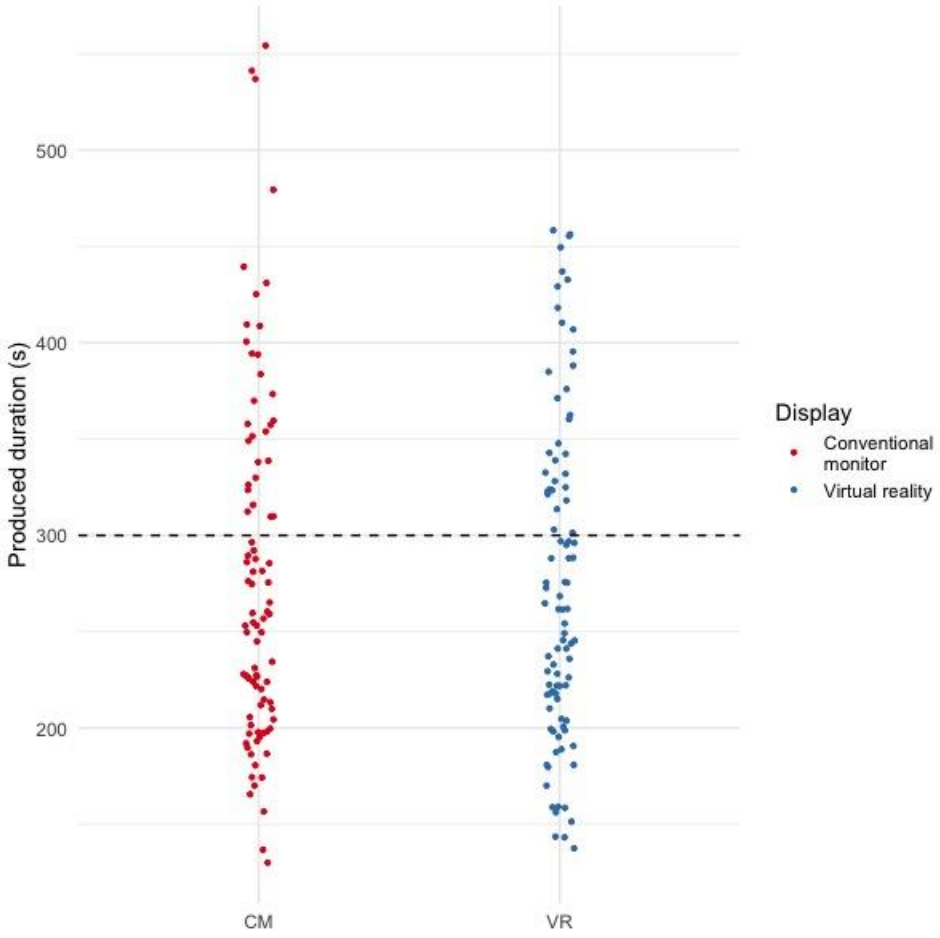

Figure 3.2 Experiment 2 produced interval durations. The dashed line represents the duration that participants were instructed to produce (5 minutes). Horizontal jitter has been added to the dots for clarity. Maze sets A and B are collapsed.

After Levene's test verified that produced durations had homogeneity of variance across the four groups ($F(1, 182) = 0.08$, $p > .5$), I conducted a two-way ANOVA using display type (VR or CM) and maze set (A or B) as factors. There was no significant main effect of display type ($F(1, 178) = 0.046$, $p > .5$, $\eta^2_G < .001$). This finding is inconsistent with both Mullen and

Davidenko's (2021) reported underestimation in VR effect and the overestimation in VR effect observed in Experiment 1.

As expected based on Mullen and Davidenko (2021), there was no main effect of maze set ($F(1, 178) = 0.90$, $p = .34$, $\eta^2_G = .0050$) and no interaction between display type and maze set ($F(1, 178) = 0.048$, $p > .5$, $\eta^2_G < .001$).

There was a main effect of display type on practice time, such that participants in the VR conditions spent more time practicing than those in CM conditions ($F(1, 178) = 13.36$, $p < .001$, $\eta^2_G = .070$). This is the opposite relationship from what was observed in Experiment 1. Practice time was not significantly different between maze sets ($F(1, 178) = 13.36$, $p = .49$, $\eta^2_G = .0026$).

The rate at which participants progressed through levels of the game within each display group was calculated with the same bootstrap method used for Experiment 1. The 95% confidence interval of the VR group's slope [0.018, 0.021] was slightly above that of the CM group [0.014, and 0.018]. This means that participants tended to complete levels at a faster rate in VR.

3.2.1 Comparing Experiment 1 with Experiment 2

I compared interval durations between Experiments 1 and 2 in order to probe the difference in display effect results. Intervals from Experiment 1's 10-minute conditions were excluded, as Experiment 2 had no corresponding groups to directly compare with them. Levene's test showed that the five-minute conditions had homogenous variance across the two experiments ($F(3, 232) = 1.02$, $p = .38$), so I conducted a two-way ANOVA with display type (VR or CM) and experiment (1 or 2) as factors. There was a significant effect of experiment

($F(1, 232) = 4.40$, $p = .037$, $\eta^2_G = .019$) such that intervals tended to be longer in Experiment 2 than in Experiment 1's five-minute conditions. There was no significant main effect of display ($F(1, 232) = 1.32$, $p = .25$, $\eta^2_G = .0056$) and no significant interaction between experiment and display ($F(1, 232) = 0.73$, $p = .39$, $\eta^2_G = .0031$).

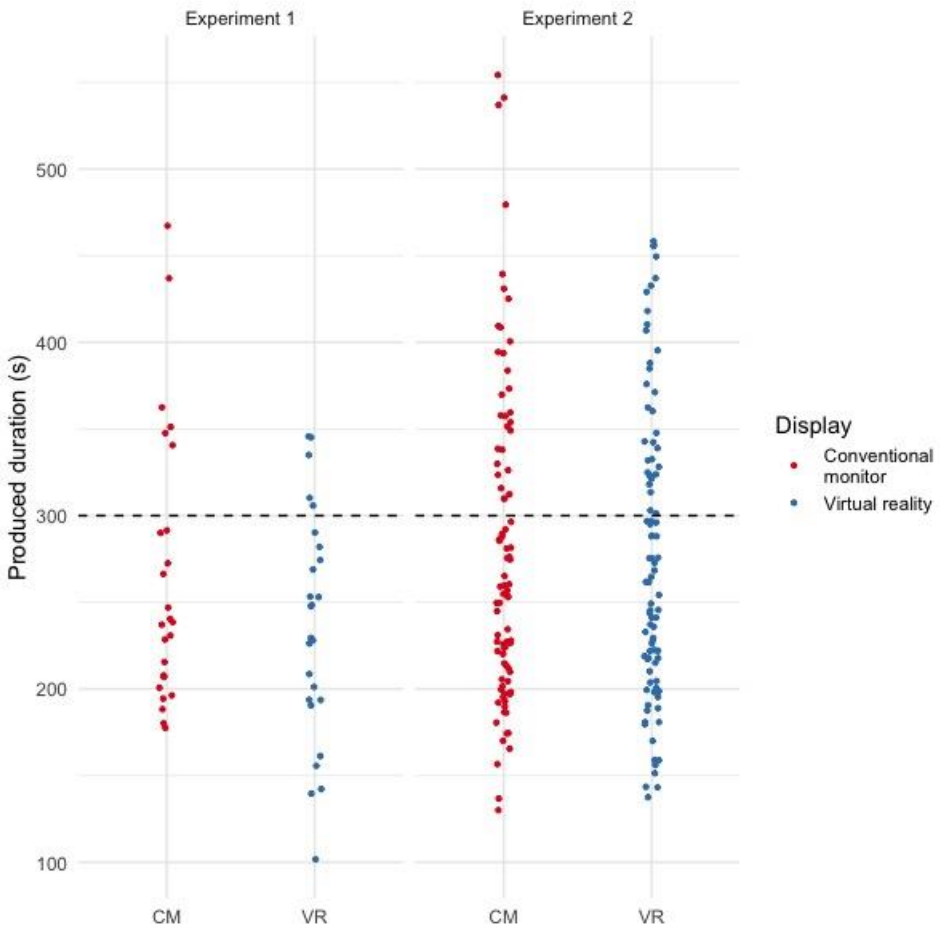

Figure 3.2.1 Produced interval durations in 5-minute conditions, Experiments 1 and 2. Data from participants instructed to produce 10-minute intervals in Experiment 1 are not included. The black dashed line represents the duration that participants were instructed to produce (5 minutes). Horizontal jitter has been added to the dots for clarity.

Despite the lack of a significant interaction effect, planned contrasts were conducted to test if one display group exhibited more change between experiments than the other display group. This was to investigate whether changes to the virtual camera size in VR may have impacted interval production. Notably, virtual camera size was the only change to the virtual environment that selectively impacted its appearance in VR: all other changes to the task and stimuli between Experiments 1 and 2 were applied equally to both display conditions.

Contrasts showed that intervals produced in VR were significantly longer in Experiment 2 than in Experiment 1 ($t(232) = 2.093$, $p = .037$, $d = 0.49$), while intervals produced in CM were not significantly different between experiments ($t(232) = 0.88$, $p = .38$, $d = 0.19$), indicating that the main effect of experiment was driven mostly by changes in VR conditions. This suggests that participants underestimated time (i.e., produced longer intervals) when the virtual camera was larger, and overestimated time (i.e., produced shorter intervals) when the virtual camera was smaller.

3.2.2 Questionnaire Results

Participants rated the VR condition as significantly more immersive than the CM condition ($t(36.1) = 3.20$, $p = .0028$, $d = 1.0$). The VR version of the game was also rated as less difficult ($t(180.92) = -3.68$, $p < .001$, $d = 0.54$). Participants were equally confident in the accuracy of their time perception between display conditions ($t(182) = -0.13$, $p > .5$, $d = 0.020$).

Perceived size of the marble was extremely variable ($M = 92$ cm in diameter, $SD = 227$ cm) and not different between display conditions ($t(118.54) = 0.30$, $p > .5$, $d = 0.045$). Questions asking for size estimates were open-ended and many responses were excluded for ambiguity. Perceived size of the virtual room was not analyzed as it was evident from written responses that

many participants interpreted the question as being about the size of the maze (which varied between levels) rather than the room around it. I was unable to selectively exclude these responses because most participants did not specify whether they estimated the size of a maze or the size of the room.

Participants in the VR condition were marginally more concerned about exposure to COVID-19 during the experiment, ($t(160.46) = 1.97$, $p = .051$, $d = 0.29$), but concern about exposure to COVID-19 was not correlated with produced interval duration in either the VR group ($r(92) = -.031$, $p > .5$) or the CM group ($r(88) = .052$, $p > .5$).

Out of 184 participants who completed the questionnaire, 53 reported that they wore a mask, and four reported that they wore a mask "some of the time." In the VR condition, participants who wore masks reported marginally more lens fog ($t(33.92) = -1.76$, $p = .087$, $d = 0.46$), but interval durations produced in VR were not different between masked and unmasked participants ($t(45.96) = -0.34$, $p > .5$, $d = 0.076$).

Participants in Experiment 2 did not rate themselves as significantly more or less familiar with VR than participants in Mullen and Davidenko (2021)'s experiment ($t(52.34) = 0.79$, $p = .43$, $d = 0.14$).

3.3 Discussion

Using the same materials and interval production task as Mullen and Davidenko's (2021) study with substantially higher statistical power, Experiment 2 failed to replicate their results. Recall that Mullen and Davidenko (2021) reported an *under*estimation effect in VR, the current study's Experiment 1 found an *over*estimation effect in VR, and Experiment 2 found no effect of

VR. Collectively, these results indicate that VR does not produce a general and reliable effect on prospective time estimation.

However, the significant difference in intervals produced in VR between Experiments 1 and 2 suggests that VR may affect time estimation in a way that depends on virtual camera size. The two experiments sampled participants from the same population with few methodological differences. The only change that was exclusively applied to the VR condition, and therefore seems likely to account for VR intervals but not CM intervals being longer in Experiment 2, was virtual camera size.

The size of a virtual camera changes the appearance of the environment in VR, but has no impact on the appearance of the environment when displayed on a conventional monitor. It determines binocular disparity and the magnitude of camera movement in response to head movement in VR. When viewing an environment through a larger virtual camera, the difference in angle between the images presented to the user's left and right eyes in VR is increased, and head movements in real space translate to more movement through the virtual environment. Both factors are cues to the user's size relative to the virtual environment, such that a large virtual camera gives the impression that the user is large and/or the environment is small.

It is striking that the VR version of the game was rated as easier, and participants were able to progress through levels in it more quickly than in CM conditions. There was no difference in game difficulty or performance in Experiment 1. Making the maze appear larger appears to have made the VR game easier than the CM version, while no difference is observed when the retinal sizes of the mazes were matched. This could account for participants producing shorter intervals in VR in Experiment 1 (when the maze and surrounding environment appeared

smaller) in comparison with Experiment 2. The effect of virtual camera size on time estimation in VR and the potential mediating role of game difficulty are tested directly in Experiment 3.

Practice times were significantly longer in VR than in CM conditions in Experiment 2, despite the opposite relationship having been observed in Experiment 1. As noted earlier, recorded practice durations were sensitive to many extraneous variables and did not reliably measure actual time spent practicing. Neither of the two observed effects of display type on practice time can therefore be interpreted with confidence.

Post-task questions about COVID-19 concern and discomfort associated with mask-wearing did not reveal any evidence that these factors interfered with produced interval durations or that concerns or discomfort were significantly worse in VR. However, these questions were not asked in Experiment 1. Data for Experiment 1 was collected in early 2022, soon after Canada's most severe peak in COVID-19 cases (World Health Organization, n.d.) when students were still required to wear masks on campus when indoors with other people (Ono and Cormack, 2022). By the beginning of data collection for Experiment 2 in the fall of 2022, there were far fewer daily cases and masks were no longer required. Although the possibility remains that fear of COVID-19 exposure or discomfort associated with mask-wearing contributed to participants producing shorter intervals (especially in the VR conditions) in Experiment 1, Experiment 2 found no evidence that these factors have a significant impact on the interval production task.

Participants in Experiment 2 did not rate their familiarity with VR as significantly higher or lower than Mullen and Davidenko's (2021) participants did in response to the same question. This makes it unlikely that novelty effects can account for the differences in results between Mullen and Davidenko's (2021) study and the present one.

The VR condition was rated by participants as significantly more immersive than the CM condition. Mullen and Davidenko (2021) previously found no difference using the same immersion scale, interval production task, and stimuli. This difference between studies is likely because Mullen and Davidenko's (2021) participants produced intervals in both display conditions before answering the questionnaire, but each participant in the present study was exposed to only one display type. Mullen and Davidenko (2021) suggested that participants' questionnaire responses pertaining to one display may have been biased by their experience with the other because of their experiment's within-subjects design. The present results support this interpretation and further emphasize the value of using between-subjects comparisons to avoid order effects or contamination when measuring sensitive variables.

Chapter 4: Experiment 3

Experiment 3 tests the effect of virtual camera size on time estimation in VR. Participants were assigned to one of three virtual camera size conditions (small, medium, or large), all in VR. The apparent size of the virtual environment is inversely proportional to the size of the virtual camera. A 10-minute interval production task was chosen because in Experiment 1, 10-minute conditions appeared to be more sensitive to the display effect than 5-minute conditions were.

I hypothesized that participants would produce longer intervals in smaller virtual camera conditions. In other words, I expected participants to comparatively underestimate time when the environment appeared larger and overestimate time when the environment appeared smaller. This result would support my suggestion that differences in camera size contributed to intervals produced in VR (but not CM) conditions being significantly longer in Experiment 2 than in Experiment 1.

4.1 Methods

4.1.1 Participants

Data were collected from 248 undergraduate psychology students at the University of British Columbia who received course credit for their participation. I excluded data from 19 participants due to procedural errors, and seven who produced outlier data (according to the IQR rule). This left the final analysis with 222 participants (81.1% women, $M_{age} = 20.5$, $SD = 2.6$).

4.1.2 Stimulus

The 30-level maze set from Experiment 1 was modified for use in Experiment 3. The size of the virtual camera was manipulated across three conditions: small, medium, and large (with scale factors of 1, 10, and 30, respectively). When the virtual camera is bigger, binocular disparity is increased and head movement through real space translates to greater camera movement through virtual space (a head movement that shifts the user's perspective all the way to the boundary of the virtual environment when the camera is large may barely change the user's perspective when the camera is small).

The virtual camera was manipulated in Unity via the "XR Rig," which is a game object that governs the user's perspective in VR and how it is manipulated via head movement. Its scale and position are coupled to the virtual camera. Enlarging the XR Rig raises the camera and moves it forward by default, so the XR Rig's location in the game environment was offset to match the position of participants' point of view between conditions.

Virtual camera size condition	XR Rig scale factor	Apparent marble size (diameter)	Apparent room size (width x depth x height)
Small	1	60cm	30m x 30m x 22.5m
Medium	10	6cm	3m x 3m x 2.25m
Large	30	2cm	1m x 1m x 0.75m

Table 4.1.2 Apparent dimensions in each of the three camera size conditions in Experiment 3. The XR Rig used in Experiment 1 had a scale factor of 3, while the one used in Experiment 2 had a scale factor of 1.

4.1.3 Apparatus

As in the VR conditions of Experiment 1, the game was displayed on a Meta Quest 2, and participants used a Logitech F710 Wireless Gamepad to control the game.

4.1.4 Questionnaire

The post-task questionnaire included the same presence scale as Experiment 2, adapted from Slater and Steed (2000). It also asked individual questions about the participant's experience of the task and their level of experience with video games and VR. To gauge how much the perceived size of the environment was affected by the virtual camera scale, it also asked participants to estimate the size of the marble and the distance between the left and right walls of the environment (reworded to be less ambiguous than in Experiment 2, when similar questions were often misinterpreted). Appendix C presents a complete list of all questionnaire items used in Experiment 3.

4.1.5 Procedure

Participants were assigned one of three virtual camera size conditions (small, medium, or large—all in VR) and were instructed to play the maze game for 10 minutes. The procedure was otherwise identical to Experiments 1 and 2.

4.2 Results

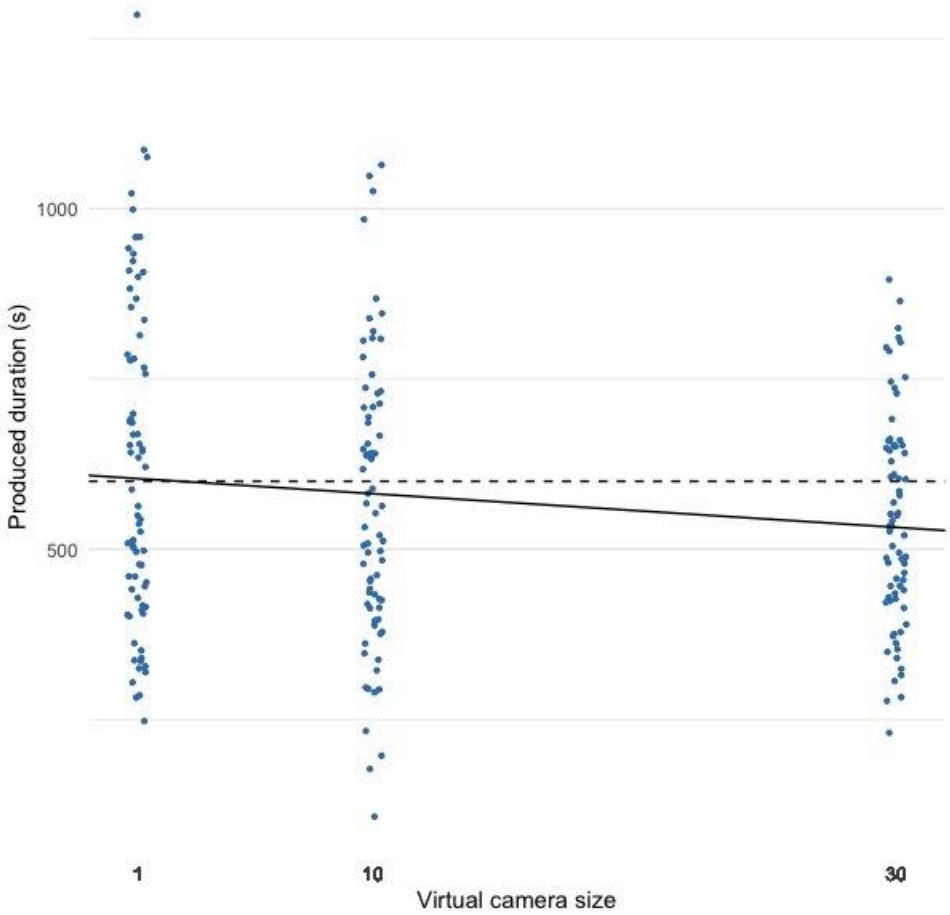

Figure 4.2 Produced interval durations by virtual camera size in Experiment 3. Horizontal jitter was added to the dots for clarity. A regression line is superimposed.

Produced durations across the three camera size conditions showed highly heterogenous variance according to Levene's test ($F(2, 219) = 7.16$, $p < .001$). However there were 74 participants in each group, and ANOVA is generally considered robust to violations of homogeneity of variance when group sizes are balanced (Blanca et al., 2018). A one-way ANOVA indicated that virtual camera size had a small but significant effect on produced interval duration ($F(2, 219) = 3.19$, $p = .043$, $\eta^2_G = .028$). Trend analysis revealed a significant linear

trend ($F(1, 219) = 5.86$, $p = .016$), such that intervals were shorter when the camera was larger. There was no significant quadratic trend ($F(1, 219) = 0.53$, $p = .47$). Practice time was not significantly different between camera size groups ($F(2, 219) = 0.89$, $p = .41$, $\eta^2_G = .008$).

The rate at which participants progressed through maze levels was calculated with the same bootstrap method used in Experiments 1 and 2. The 95% confidence intervals of the slopes for the small [0.014, 0.018], medium [0.015, 0.018], and large [0.013, 0.017] camera size groups all overlapped. The size of the virtual camera appears not to have significantly affected participants' game performance.

4.2.1 Questionnaire Results

Virtual camera size had a significant impact on participants' rated difficulty of the game ($F(2, 219) = 3.59$, $p = .029$, $\eta^2_G = .032$). Trend analysis showed that there was a significant linear trend, such that the larger camera size conditions were rated as more difficult ($F(1, 219) = 5.834$, $p = .017$). There was no significant quadratic trend ($F(1, 219) = 1.35$, $p = .25$). However, rated difficulty was not correlated with produced interval duration ($r(220) = .028$, $p > .5$) and was not a significant predictor of interval duration ($R^2_{adj} = -.0037$, $F(1, 220) = 0.18$, $p > .5$). This suggests that difficulty did not mediate the effect of virtual camera size on duration judgment.

The effect of virtual camera size on presence ratings did not reach significance ($F(2, 219) = 2.59$, $p = .078$, $\eta^2_G = .023$). Self-reported comfort during the task was also not significantly different between conditions ($F(2, 219) = 0.13$, $p > .5$, $\eta^2_G = .0012$).

Unexpectedly, there was no difference between camera size conditions in perceived marble size ($F(2, 212) = 0.96$, $p = .39$, $\eta^2_G = .009$) or perceived distance between the left and right walls of the room ($F(2, 192) = 2.63$, $p = .075$, $\eta^2_G = .027$). Each camera size simulates

specific dimensions of the environment as it appears in VR (see Table 4.1.2), but the differences in environment size were evidently not obvious to participants.

4.3 Discussion

The results support the hypothesis that participants tend to underestimate time in VR when the environment appears larger, and to overestimate time when the environment appears smaller. This effect may have contributed to the fact that a VR-induced overestimation effect was only observed when the camera was larger (in Experiment 1), and a VR-induced underestimation effect was only observed when the camera was smaller (Mullen and Davidenko, 2021).

The heterogeneity of variance in produced durations between camera size groups is remarkable. Variance in the small camera group (*SD* = 235.88) is higher than in the medium group (*SD* = 209.08), which is still much higher than the large group (*SD* = 152.91 seconds). This is possibly the result of a floor effect that keeps the lower end of each group's distribution relatively insensitive to manipulation while the upper ends of the distributions decrease as camera size increases. Individual differences in susceptibility to the influence of virtual camera or environment size, which may also have contributed to this, could be tested by a repeated measures experiment.

Game difficulty was rated as higher in larger camera size conditions, when the maze appeared smaller. This corresponds with the VR game having been rated as easier than its CM counterpart in Experiment 2 (when the maze appeared larger in VR) but not in Experiment 1 (when there was no difference in apparent maze size). However, the rate of participants' progress through levels was not affected by virtual camera size in Experiment 3. Additionally, rated game

difficulty was not significantly correlated with or predictive of produced interval durations. This suggests that the influence of virtual camera size on time estimation is not explained by a mediating difficulty effect. There is likely some other aspect of virtual camera size, separate from its effect on difficulty, that distorts time estimation.

Questionnaire responses showed that perceived room and marble size were not significantly different between the three camera size conditions. That a manipulation of virtual camera/environment size should affect time estimation but not size estimation is surprising. This might be because the environment was somewhat abstract and did not include an obvious size reference (e.g., a door or a person). Participants were also not required to move their heads to progress through the game, so the head-tracking cue to size may not have been very noticeable. Assigning veridical dimensions to an abstract virtual environment viewed from a practically stationary angle may have been too difficult. I expect that participants would be able to rank the three environments by apparent size easily if they were shown all three, but that kind of comparison is precluded in a between-subjects design.

The finding that participants underestimated time when the environment appeared large and overestimated time when the environment appeared small seems to contradict a fairly consistent pattern observed in previous work. Aside from the rare exception (Predebon, 2002), most studies using temporal reproduction methods have found that people overestimate the presentation time of large stimuli compared to small stimuli (Rammsayer and Verner, 2014), including virtual environments (Riemer et al., 2018) and even stimuli whose size is implicit or imagined (Birngruber and Ulrich, 2019). The present study's results might be reconciled with these opposite findings by differences in measures of time estimation.

Temporal *re*production may be critically different from interval production in experiments like these. Although temporal reproduction tasks can measure prospective estimation when the participant is informed before the reference interval, they necessarily rely on memory more than interval production does. Temporal reproduction involves storing information about a target interval while it elapses, and then attempting to reproduce the same duration from memory after it ends.

Rammsayer and Verner (2015) found that stimulus size only impacts temporal reproduction when size is varied during the reference interval, not during the reproduction phase. The authors propose that stimulus size does not directly affect the "internal clock" thought to be at the core of prospective timekeeping, but rather the estimator's storage of the reference duration in memory. It is difficult to apply this theory to interval production, which has no separation between the production phase and the interval being estimated. But if interval production is less dependent on memory-related processes than interval reproduction, it should also be less sensitive to memory-related manipulation.

Another key difference between interval production and reproduction tasks is that the former is better suited for estimation of longer intervals. Whereas participants in this study were instructed to produce intervals of 5 and 10 minutes, the temporal reproduction studies that have associated large stimuli with overestimation of time typically study intervals in the range of 50 milliseconds to 5 seconds (Rammsayer and Verner, 2014). According to Block and Gruber (2014), different processes are involved in the estimation of shorter and longer intervals, and there may be a critical threshold at about 3-5 seconds.

That time perception is generally influenced by spatial perception is predicted by multiple competing theories. A theory of magnitude (Walsh, 2003) posits that magnitudes of space, time,

and number are processed by a common system, and that perception of magnitude in any one domain can influence perception of magnitude in others. Metaphor structuring (Boroditsky, 2000; Lakoff and Johnson, 1980) instead proposes an asymmetrical relationship between temporal and spatial perception, by which perception of space serves as a foundation for perception of time and other higher-level concepts. This is based on linguistic evidence that our understanding of time is based on spatial metaphors (e.g., "a *long* time ago"), as well as experimental findings that irrelevant spatial information influences duration judgments, but irrelevant temporal information does not reciprocally influence spatial judgments (Casasanto and Boroditsky, 2008).

There is also evidence that temporal and spatial information are encoded by overlapping neuronal substrates. Hippocampal "time cells" have been observed to encode information about both time and distance (Kraus et al., 2013; MacDonald et al., 2011). Grid cells, primarily identified as being involved in spatial navigation, can also encode duration (Kraus et al., 2015).

In sum, there is substantial evidence that time perception can be manipulated by nontemporal information related to space and size. However, little is known about how this interference occurs, and to what extent it depends on the method of time estimation. The present results suggest that a long interval production task may elicit opposite effects from a short reproduction task.

Chapter 5: Conclusion

5.1 Summary

The objectives of this thesis were to test the reliability of a previously reported time underestimation effect in virtual reality (Mullen & Davidenko, 2021), and to identify factors that potentially mediate the effect. In Experiment 1 participants played a video game for a target duration of 5 or 10 minutes, either in VR or on a conventional monitor. Contrary to the hypothesis that participants would underestimate time in VR, the VR group *over*estimated time compared to the CM group.

To find out if the difference in results between Experiment 1 and Mullen & Davidenko's (2021) study hinged on a methodological deviation, Experiment 2 was conducted as an exact replication of Mullen and Davidenko's (2021) methods. The results did not reproduce Mullen & Davidenko's (2021) finding of time underestimation in VR; Experiment 2 found no significant effect of display type on time estimation.

A significant difference in VR intervals between Experiments 1 and 2 indicated that the change in methods may have selectively impacted time estimation in the VR conditions. Experiment 3 tested the role of virtual camera size in VR, finding that participants tended to comparatively underestimate time when the camera was small (making the environment appear large) and overestimate time when the camera was large (making the environment appear small).

5.2 General Discussion

The results of Experiments 1 and 2 call into serious question the existence of a VR-induced time underestimation effect. They corroborate what studies that have used verbal

estimation methods (Schatzschneider et al., 2016; Bruder and Steinicke, 2014; van der Ham et al., 2019) have found: that prospective time estimation is not generally altered in VR. Yet the absence of an *inherent* effect of VR (i.e., when content is matched between displays) does not preclude the possibility that there are factors unique to VR that may be manipulated to affect time estimation. As Experiment 3 shows, the apparent size of a VR environment can affect how we estimate time inside it.

The size effect observed in Experiment 3 may have contributed to Experiment 2's VR group (who viewed the environment through a smaller virtual camera) producing significantly longer intervals than Experiment 1's VR group. However, Experiment 3's size manipulation was more extreme than the size differences between any prior experiments, and the observed effect of virtual camera size was small. Changes to virtual camera size are not sufficient to explain the inconsistency of findings concerning the effect of VR on time estimation. Factors related to COVID-19 might have played a compounding role: participant testing for Experiment 1 (when intervals produced in VR were particularly short) was conducted close to the height of the pandemic in Canada. This is only speculative, but it seems plausible that participants ended their intervals sooner during this period because they were less comfortable using a shared VR headset.

There are important differences between commercial VR content and laboratory stimuli. Commercial VR experiences can appear limitlessly vast and surround the user with salient content in all directions. Controlled stimuli like the ones used in this study are relatively small, and all the content relevant for the participants' task can be easily viewed from a single, stationary head position. Both the scale of the environment and the retinal size of the area that

the user visually explores tend to be much larger in commercial VR experiences than in VR stimuli designed for controlled experiments.

In the Introduction and in my previous study (Mullen & Davidenko, 2021), I included part of the following quote from a VR developer: "…time passes differently in VR. You think you've played for 15 minutes and then you go out and it's like, 'wait, I spent an hour in there?' There's a concept of, I don't know, VR time" (Miller, 2016). Notably, that developer was speaking about a VR game set in deep space, where players fly spaceships around an environment with no visible boundaries, and celestial bodies loom in the distance.

It may specifically be these vast virtual spaces that have elicited informal reports of time seeming to pass quickly in VR. Controlled experiments may have failed to find consistent evidence of this effect because the kind of VR environment that can cause significant underestimation of time is not the kind that can be easily matched by a non-VR control group.

5.3 Limitations and Future Work

The variability of this study's produced duration data is exceedingly high. Experiment 3 in particular had extremely high variance and heterogeneity of variance between groups. Follow-up experiments could attempt to limit statistical noise by giving more specific instructions and emphasizing that participants should prioritize producing an accurate interval over making progress through the game.

The stimuli used in these experiments were all variations of the same virtual environment, one that in fundamental ways is unrepresentative of virtual reality experiences outside the laboratory. The design of the stimuli largely compromised ecological validity in favor of maintaining strict experimental control between display conditions. Whereas most commercial

VR games allow users to walk around the room and encourage them to look in all directions, the maze game was designed to be played while seated at a desk, facing forward. I made sure that no body movements (except for pressing buttons on a gamepad) were necessary to interact with the game in VR so that it could be directly compared to a desktop monitor counterpart. This helped limit potential confounding variables, but also limited the generalizability of the results to real-world VR use.

Future experiments interested in general effects of VR should use expansive virtual environments that are more representative of non-laboratory VR experiences. While these would be difficult to strictly compare with conventional displays, real-world control conditions might be used instead. For example, participants exploring a real room could be compared with participants exploring a 3D model of the same room in VR. This could isolate the inherent effects of VR use (e.g., wearing a headset, not being able to see one's own body, contextual knowledge that the environment is virtual) while matching realistic mobility and environment appearance across conditions.

Questions remain as to what kinds of size manipulations matter for the effect observed in Experiment 3. The virtual camera size manipulation simultaneously affected the apparent dimensions of the virtual room, binocular disparity, head-tracking, the participants' sense of their own size, and the retinal size of the maze. It would be valuable to isolate these and other individual cues to size in VR (such as avatar size and perspective height) to test their influences on time estimation separately.

It would also be informative to manipulate the distribution of content around the user in a virtual environment. One of the most characteristic features of VR is that users must move their eyes and head extensively to see all of an environment's content, while less eye movement and

practically no head movement is involved in viewing content on a conventional monitor. I did not measure eye movements in this study, but more eccentric eye movements were necessary to play the maze game when the virtual camera was smaller. Yet even in the smallest of the three camera size conditions, the field over which participants had to move their eyes was much more limited than in most commercial VR experiences. It would be worth testing if the effect of VR environment size on time estimation is mediated by eye movements.

No data was collected about mask-wearing behavior or attitudes towards COVID-19 during Experiment 1. This unfortunately prevents me from testing my conjectures about how these factors may have impacted participants' interval production, and new experiments cannot retrospectively investigate participants' discomfort or fear of exposure with much accuracy.

This study only tested estimation of 5- and 10-minute intervals. Research indicates that estimation of shorter periods may depend on fundamentally different processes (Block and Gruber, 2014). Comparable tests at other time scales may help delineate how the effect of virtual environment size on time estimation may depend on the length of the estimated interval.

Existing VR experiences used for distraction therapy and other applications that seek to make time fly can be modified to test their impact on time estimation at different environment sizes. Based on the results of Experiment 3, such applications may find more success with large virtual spaces that encourage visual exploration of a wide area. Games with large-scale environments may likewise be the most capable of causing time loss during recreational VR use.

References

Bar-Haim, Y., Kerem, A., Lamy, D., & Zakay, D. (2010). When time slows down: The influence of threat on time perception in anxiety. *Cognition and emotion, 24*(2), 255-263. https://doi.org/10.1080/02699930903387603

Birngruber, T., & Ulrich, R. (2019). Perceived duration increases not only with physical, but also with implicit size. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*, 969–979. https://doi.org/10.1037/xlm0000628

Blanca, M. J., Alarcón, R., Arnau, J., Bono, R., & Bendayan, R. (2018). Effect of variance ratio on ANOVA robustness: Might 1.5 be the limit? *Behavior Research Methods*, *50*, 937-962. https://doi.org/10.3758/s13428-017-0918-2

Block, R. A., & Gruber, R. P. (2014). Time perception, attention, and memory: A selective review. *Acta Psychologica*, *149*, 129–133. https://doi.org/10.1016/j.actpsy.2013.11.003

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. https://doi.org/10.1016/j.actpsy.2010.03.006

Block, R. A., & Reed, M. A. (1978). Remembered duration: Evidence for a contextual-change hypothesis. Journal of Experimental psychology: *Human Learning and memory, 4*(6), 656. https://doi.org/10.1037/0278-7393.4.6.656

Block, R. A., & Zakay, D. (1997). Prospective and retrospective duration judgments: A meta-analytic review. *Psychonomic Bulletin & Review*, *4*(2), 184–197. https://doi.org/10.3758/BF03209393

Boroditsky, L. (2000). Metaphoric structuring: Understanding time through spatial metaphors. *Cognition*, *75*(1), 1–28. https://doi.org/10.1016/S0010-0277(99)00073-6

Bruder, G., & Steinicke, F. (2014). Time perception during walking in virtual environments. *2014 IEEE Virtual Reality (VR)*, 67–68. https://doi.org/10.1109/VR.2014.6802054

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition*, *106*(2), 579–593. https://doi.org/10.1016/j.cognition.2007.03.004

Chirico, A., D'Aiuto, M., Pinto, M., Milanese, C., Napoli, A., Avino, F., Iodice, G., Russo, G., De Laurentiis, M., Ciliberto, G., Giordano, A., & Lucidi, F. (2016). The Elapsed Time During a Virtual Reality Treatment for Stressful Procedures. A Pool Analysis on Breast Cancer Patients During Chemotherapy. In G. D. Pietro, L. Gallo, R. J. Howlett, & L. C. Jain (Eds.), *Intelligent Interactive Multimedia Systems and Services 2016* (pp. 731–738). Springer International Publishing. https://doi.org/10.1007/978-3-319-39345-2_65

D. Griffiths, M., J. Kuss, D., & L. King, D. (2012). Video Game Addiction: Past, Present and Future. *Current Psychiatry Reviews*, *8*(4), 308–318. https://doi.org/10.2174/157340012803520414

Droit-Volet, S., & Wearden, J. (2016). Passage of Time Judgments Are Not Duration Judgments: Evidence from a Study Using Experience Sampling Methodology. *Frontiers in Psychology*, *7*. https://www.frontiersin.org/article/10.3389/fpsyg.2016.00176

Griffiths, M. D., Kuss, D. J., & King, D. L. (n.d.). Video Game Addiction: Past, Present and Future. *Current Psychiatry Reviews*, *8*(4), 308–318.

Hornik, J. (1992). Time estimation and orientation mediated by transient mood. *The Journal of Socio-Economics*, *21*(3), 209–227. https://doi.org/10.1016/1053-5357(92)90010-5

Ioannidis, J. P. A. (2005). Why Most Published Research Findings Are False. *PLOS Medicine*, *2*(8), e124. https://doi.org/10.1371/journal.pmed.0020124

Kraus, B. J., Brandon, M. P., Robinson, R. J., Connerney, M. A., Hasselmo, M. E., & Eichenbaum, H. (2015). During Running in Place, Grid Cells Integrate Elapsed Time and Distance Run. *Neuron*, *88*(3), 578–589. https://doi.org/10.1016/j.neuron.2015.09.031

Kraus, B. J., Robinson, R. J., White, J. A., Eichenbaum, H., & Hasselmo, M. E. (2013). Hippocampal "Time Cells": Time versus Path Integration. *Neuron*, *78*(6), 1090–1101. https://doi.org/10.1016/j.neuron.2013.04.015

Loreto-Quijada, D., Gutiérrez-Maldonado, J., Nieto, R., Gutiérrez-Martínez, O., Ferrer-García, M., Saldaña, C., Fusté-Escolano, A., & Liutsko, L. (2014). Differential Effects of Two Virtual Reality Interventions: Distraction Versus Pain Control. *Cyberpsychology, Behavior, and Social Networking*, *17*(6), 353–358. https://doi.org/10.1089/cyber.2014.0057

Lugrin, J.-L., Unruh, F., Landeck, M., Lamour, yoan, Latoschik, M. E., Vogeley, K., & Wittmann, M. (2019). Experiencing Waiting Time in Virtual Reality. *25th ACM Symposium on Virtual Reality Software and Technology*, 1–2. https://doi.org/10.1145/3359996.3364807

MacDonald, C. J., Lepage, K. Q., Eden, U. T., & Eichenbaum, H. (2011). Hippocampal "Time Cells" Bridge the Gap in Memory for Discontiguous Events. *Neuron*, *71*(4), 737–749. https://doi.org/10.1016/j.neuron.2011.07.012

Magyaródi, T., Nagy, H., Soltész, P., Mózes, T., & Oláh, A. (2013). *Psychometric properties of a newly established flow state questionnaire*.

Matthews, W. J., & Meck, W. H. (2016). Temporal cognition: Connecting subjective time to perception, attention, and memory. *Psychological bulletin*, *142*(8), 865–907. https://doi.org/10.1037/bul0000045

Miller, A. C., Hickman, L. C., & Lemasters, G. K. (1992). A Distraction Technique for Control of Burn Pain. *The Journal of Burn Care & Rehabilitation*, *13*(5), 576–580. https://doi.org/10.1097/00004630-199209000-00012

Miller, R. (2016) Oculus founder thinks VR may affect your ability to perceive time passing. *The Verge*. https://www.theverge.com/2016/3/17/11258718/palmer-luckey-oculus-time-vr-virtual-reality-gdc-2016.

Mullen, G., & Davidenko, N. (2021). Time Compression in Virtual Reality. *Timing & Time Perception*, *9*(4), 377–392. https://doi.org/10.1163/22134468-bja10034

Murray, C. D., & Gordon, M. S. (2001). Changes in bodily awareness induced by immersive virtual reality. *CyberPsychology & Behavior*, *4*(3), 365-371. https://doi.org/10.1089/109493101300210268

Nakamura, J., & Csikszentmihalyi, M. (2014). The Concept of Flow. In M. Csikszentmihalyi, *Flow and the Foundations of Positive Psychology* (pp. 239–263). Springer Netherlands. https://doi.org/10.1007/978-94-017-9088-8_16

Nuyens, F. M., Kuss, D. J., Lopez-Fernandez, O., & Griffiths, M. D. (2020). The Potential Interaction Between Time Perception and Gaming: A Narrative Review. *International Journal of Mental Health and Addiction*, *18*(5), 1226–1246. https://doi.org/10.1007/s11469-019-00121-1

Ono, S. J., & Cormack, L. (2022, March 10). *COVID-19 update: Maintaining masks in UBC public indoor spaces*. UBC Broadcast. https://broadcastemail.ubc.ca/2022/03/10/covid-19-update-maintaining-masks-in-ubc-public-indoor-spaces/

Ornstein, R. E. (1969). *On the Experience of Time*. Harmondsworth.

Predebon, J. (2002). Viewing Distance and Estimates of Duration. *Perceptual and Motor Skills*, *95*(1), 326–328. https://doi.org/10.2466/pms.2002.95.1.326

Rammsayer, T. H., & Verner, M. (2014). The effect of nontemporal stimulus size on perceived duration as assessed by the method of reproduction. *Journal of Vision*, *14*(5), 17-17. https://doi.org/10.1167/14.5.17

Rammsayer, T. H., & Verner, M. (2015). Larger visual stimuli are perceived to last longer from time to time: The internal clock is not affected by nontemporal visual stimulus size. *Journal of Vision*, *15*(3), 5-5. https://doi.org/10.1167/15.3.5

Riemer, M., Shine, J. P., & Wolbers, T. (2018). On the (a)symmetry between the perception of time and space in large-scale environments. *Hippocampus*, *28*(8), 539–548. https://doi.org/10.1002/hipo.22954

Rudd, M., Vohs, K. D., & Aaker, J. (2012). Awe Expands People's Perception of Time, Alters Decision Making, and Enhances Well-Being. *Psychological Science*, *23*(10), 1130–1136. https://doi.org/10.1177/0956797612438731

Rutrecht, H., Wittmann, M., Khoshnoud, S., & Igarzábal, F. A. (2021). Time Speeds Up During Flow States: A Study in Virtual Reality with the Video Game Thumper. *Timing & Time Perception*, *9*(4), 353–376. https://doi.org/10.1163/22134468-bja10033

Schatzschneider, C., Bruder, G., & Steinicke, F. (2016). Who turned the clock? Effects of Manipulated Zeitgebers, Cognitive Load and Immersion on Time Estimation. *IEEE Transactions on Visualization and Computer Graphics*, *22*(4), 1387–1395. https://doi.org/10.1109/TVCG.2016.2518137

Schneider, S. M., Kisby, C. K., & Flint, E. P. (2011). Effect of virtual reality on time perception in patients receiving chemotherapy. *Supportive Care in Cancer*, *19*(4), 555–564. https://doi.org/10.1007/s00520-010-0852-7

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1535), 3549–3557. https://doi.org/10.1098/rstb.2009.0138

Slater, M., & Steed, A. (2000). A Virtual Presence Counter. *Presence: Teleoperators and Virtual Environments*, *9*(5), 413–434. https://doi.org/10.1162/105474600566925

Sucala, M., Scheckner, B., & David, D. (2011). Psychological Time: Interval Length Judgments and Subjective Passage of Time Judgments. *Current Psychology Letters. Behaviour, Brain & Cognition, Vol. 26, Issue 2, 2010*, Article Vol. 26, Issue 2, 2010. https://doi.org/10.4000/cpl.4998

Unruh, F., Landeck, M., Oberdörfer, S., Lugrin, J.-L., & Latoschik, M. E. (2021). The Influence of Avatar Embodiment on Time Perception—Towards VR for Time-Based Therapy. *Frontiers in Virtual Reality*, *2*. https://www.frontiersin.org/articles/10.3389/frvir.2021.658509

Usoh, M., Catena, E., Arman, S., & Slater, M. (2000). Using Presence Questionnaires in Reality. *Presence: Teleoperators and Virtual Environments*, *9*(5), 497–503. https://doi.org/10.1162/105474600566989

van der Ham, I. J. M., Klaassen, F., van Schie, K., & Cuperus, A. (2019). Elapsed time estimates in virtual reality and the physical world: The role of arousal and emotional valence. *Computers in Human Behavior*, *94*, 77–81. https://doi.org/10.1016/j.chb.2019.01.005

Vatakis, A., Balci, F., Di Luca, M., & Correa, Á. (Eds.). (2018). *Timing and time perception: Procedures, measures, and applications*. Brill.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*(11), 483–488. https://doi.org/10.1016/j.tics.2003.09.002

World Health Organization. (n.d.). *Canada: WHO Coronavirus Disease Dashboard.* https://covid19.who.int/region/amro/country/ca

Wiener, M., & Thompson, J. C. (2016). The effect of background context on the size–time illusion. *Timing & Time Perception*, *4*(2), 167-186. https://doi.org/10.1163/22134468-00002065

Wood, R. T. A., Griffiths, M. D., & Parke, A. (2007). Experiences of Time Loss among Videogame Players: An Empirical Study. *CyberPsychology & Behavior*, *10*(1), 38–44. https://doi.org/10.1089/cpb.2006.9994

Yang, J., Rahardja, S., & Fränti, P. (2019a). Outlier detection: How to threshold outlier scores? *Proceedings of the International Conference on Artificial Intelligence, Information Processing and Cloud Computing*, 1–6. https://doi.org/10.1145/3371425.3371427

Yang, J., Rahardja, S., & Fränti, P. (2019b). Outlier detection: How to threshold outlier scores? *Proceedings of the International Conference on Artificial Intelligence, Information Processing and Cloud Computing*, 1–6. https://doi.org/10.1145/3371425.3371427

Zakay, D., & Block, R. A. (n.d.). *An Attentional·Gate Model of Prospective Time Estimation*.

Zakay, D., & Block, R. A. (1996). The role of attention in time estimation processes. In M. A. Pastor & J. Artieda (Eds.), *Advances in Psychology* (Vol. 115, pp. 143–164). North-Holland. https://doi.org/10.1016/S0166-4115(96)80057-4

Appendices

Appendix A Experiment 1 Questionnaire

All items required responses. Reverse-coded items are marked with an asterisk.

A.1 Bodily awareness (adapted from Murray and Gordon, 2001)

Please rate your awareness on each of the characteristics described below. Select the answer that most accurately described how you felt during the experiment.

While playing the game I was aware of:

For each of the following items, participants were required to select a number from the following scale: Never [1] [2] [3] [4] [5] Always

1. Swallowing frequently
2. A ringing in my ears
3. Sensations of prickling, tingling, or numbness in my body
4. An urge to cough to clear my throat
5. My mouth being dry
6. Being exhausted
7. Needing to rest
8. How fast I was breathing
9. Watering or tearing of my eyes

10. Eye fatigue or pain

11. Rolling or fluttering of my eyes

12. A swelling of my body or parts of my body

13. Muscle tension in my arms and legs

14. Muscle tension in my back and neck

15. Facial twitches

16. Muscle pain

17. Joint pain

18. Back pain

19. Muscle tension in my face

20. Goose bumps

21. My palms sweating

22. Sweat on my forehead

23. Tremor in my lips

24. Tremor in my hands

25. My skin itching

26. My nose itching

27. Sweat in my armpits

28. The temperature of my face

29. Grinding my teeth

30. General jitteriness

31. The hair on the back of my neck “standing up”

32. Difficulty in focusing

33. My eye movements

34. An urge to swallow

35. How hard my heart was beating

A.2 Presence (adapted from Slater and Steed, 2000)

1. Please rate your sense of being in the game environment, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.

   Not at all [1] [2] [3] [4] [5] [6] [7] Very much

2. To what extent were there times during the experience when the game environment was the reality for you?

   At no time [1] [2] [3] [4] [5] [6] [7] Almost all the time

3. When you think back about your experience, do you think of the game environment more as images that you saw, or more as somewhere that you visited?

   Images that I saw [1] [2] [3] [4] [5] [6] [7] Somewhere that I visited

4. During the time of the experience, which was strongest on the whole, your sense of being in the game environment, or of being in the real laboratory room?*

Being in the game environment [1] [2] [3] [4] [5] [6] [7] Being in the real laboratory room

5. During the time of the experience, did you often think to yourself that you were actually in the game environment?

Not very often [1] [2] [3] [4] [5] [6] [7] Very much so

A.3 Flow state experience (adapted from Magyaródi et al., 2013)

For each of the following items, participants were required to select a number from the following scale: Strongly disagree [1] [2] [3] [4] [5] Strongly agree

1. I was able to keep up with the challenges
2. I felt I could meet the requirements of the situation
3. I had a grip on the events
4. I felt I was in control over the situation
5. I knew I was able to solve the task
6. I knew exactly what I had to do, and I acted accordingly
7. This task was not too difficult
8. I felt that what I had to do matched my skills well
9. I could perform effortlessly well
10. My skills were in balance with the challenges of the activity
11. My mind worked in total harmony with my body
12. My attention was not engrossed at all by the activity*
13. It was boring for me*
14. The activity totally engrossed my attention
15. I found the task interesting
16. I forgot about the progress of time
17. Time passed faster than I thought it did

18. I fused with the task

19. I forgot about my close environment

A.4 Single-item questions

1. How difficult did you find the game?

Very easy [1] [2] [3] [4] [5] Very difficult

2. During the game, how confident were you that your perception of time was accurate?

Not at all confident [1] [2] [3] [4] [5] Very confident

3. How much prior experience do you have using virtual reality?

No experience [1] [2] [3] [4] [5] Extensive experience

4. How much prior experience do you have playing video games?

No experience [1] [2] [3] [4] [5] Extensive experience

Appendix B Experiment 2 Questionnaire

All items not marked as optional required responses. Reverse-coded items are marked with an asterisk.

B.1 Single-item questions from Mullen and Davidenko (2021)

1. How difficult did you find the game you played?

   Very easy [1] [2] [3] [4] [5] Very difficult

2. How familiar are you with VR headsets?

   Not at all familiar [1] [2] [3] [4] [5] Very familiar

3. How often do you play video games?

   Not at all often [1] [2] [3] [4] [5] Very often

4. What strategies, if any, did you use to keep track of time during the interval? ***(optional)***

   [*Short answer text box*]

5. I was confident in my estimation of 5 minutes at the time that I made it.

   Strongly disagree [1] [2] [3] [4] [5] Strongly agree

B.2 Immersion scale from Mullen and Davidenko (2021)

For each of the following items, participants were required to select a number from the following scale: Strongly disagree [1] [2] [3] [4] [5] Strongly agree

1. I still felt as if I was in the real world whilst playing.*
2. I was interested to know what might be happening around me.*
3. I felt detached from the outside world.
4. Everyday thoughts and concerns were still very much on my mind.*
5. I did not feel like I was in the real world but the game world.
6. At the time the game was my only concern.
7. I still felt attached to the real world.*
8. I was aware of my surroundings.*
9. The controls were not easy to pick up.*
10. I was unaware of what was happening around me.
11. There were not any particularly frustrating aspects of the controls to get the hang of.
12. I did not like the graphics and imagery of the game.*
13. I became unaware that I was even using any controls.
14. Playing the game was not fun.*
15. Interacting with the world of the game did not feel as real to me as it would be in the real world.*
16. I did not feel the urge at any point to stop playing and see what was going on around me.
17. I enjoyed playing the game.
18. I enjoyed the graphics and imagery of the game.
19. I sometimes found myself to become so involved with the game that I wanted to speak to the game directly.

B.3 New questions

1. How clearly was the game displayed?

   [1] [2] [3] [4] [5]

2. Did you experience any kind of physical discomfort during the game? If so, please briefly describe the discomfort you experience.

   [*Short answer text box*]

3. Since June 30th, UBC has **not required** that masks be worn in indoor spaces on campus. Did you wear a mask while playing the game?

   [Yes] [No] [Some of the time]

4. In the past month, how cautious have you been about minimizing risk of exposure to COVID-19? Think of how often you wash or sanitize your hands or try to maintain social distancing.

   Not cautious at all [1] [2] [3] [4] [5] Very cautious

5. To what extent were you concerned about COVID-19 exposure while playing the game?

   Not concerned at all [1] [2] [3] [4] [5] Very concerned

6. Imagine that the game environment was a real place, and that you were inside it.

   (1) What do you think the size (depth, width, and height) of the room would be? Use metric or imperial units.

(2) What do you think the size (diameter) of the marble would be?

[*Short answer text box*]

7. If you played the game in VR: ***(optional)***

   How much lens fog (condensation buildup that makes the screen look blurrier) did you experience?

   None at all [1] [2] [3] [4] [5] A lot of lens fog

8. If you played the game in VR: ***(optional)***

   Was this your first experience using virtual reality?

   [Yes] [No]

Appendix C Experiment 3 Questionnaire

All items not marked as optional required responses.

C.1 Presence (adapted from Slater and Steed, 2000)

See Appendix A.2.

C.2 Single-item questions

1. I was confident in my estimation of 10 minutes at the time that I made it.

   Strongly disagree [1] [2] [3] [4] [5] Strongly agree

2. Do you think it's more likely that you underestimated time (played for longer than 10 minutes) or that you overestimated time (played for less than 10 minutes)?

   [Underestimated (ended after 10 minutes)] [Overestimated (ended before 10 minutes)]

   [Both seem equally likely]

3. What strategies, if any, did you use to keep track of time during the interval? ***(optional)***

   [*Short answer text box*]

4. How difficult was the game?

   Very easy [1] [2] [3] [4] [5] Very difficult

5. How fun was the game?

   Not fun at all [1] [2] [3] [4] [5] Very fun

6. How comfortable were you while playing the game?

[1] [2] [3] [4] [5]

7. If you experienced any discomfort, please describe it here. ***(optional***)

[*Short answer text box*]

8. Please estimate the size (diameter) of the marble, specifying a unity of measurement (cm, m, in, or ft).

[*Short answer text box*]

9. Please estimate the distance between the left and right walls of the virtual environment that you were in, including the unit.

[*Short answer text box*]

10. How familiar are you with VR headsets?

Not at all familiar [1] [2] [3] [4] [5] Very familiar

11. Did your head move outside the walls of the virtual room at any point? You would see a featureless gray horizon if this happened.

[Yes] [No]

12. Was this your first experience using virtual reality?

[Yes] [No]

13. Did any glitches occur during the game? Please describe them here. ***(optional)***

[*Short answer text box*]

14. How often you do play video games?

Not at all often [1] [2] [3] [4] [5] Very often