CHRONOCEPTION-DISTORTION IN VIRTUAL REALITY VARIES BY TIME PERCEPTION MODE, AND CAN BE ATTRIBUTED TO DIGITAL ENVIRONMENT AND CONTROL MECHANISMS RATHER THAN HEAD-MOUNTED DISPLAYS.

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE BY RESEARCH
in
THE SCHOOL OF EDUCATION AND SCIENCE
(Psychology)

THE UNIVERSITY OF GLOUCESTERSHIRE
(Cheltenham, Gloucestershire)

September, 2024

Abstract

Distortions in the perception of time (chronoception) have been associated with various forms of digital media and platforms. Virtual Reality (VR) has been associated with chronoception-distortion, specifically the phenomenon of 'time compression' in which an individual perceives the duration of a given interval as being shorter than its timed duration. The present study examined VR chronoception-distortion and included a number of novel approaches. An opportunity sample of 65 participants, including undergraduate students and members of the public, participated in an independent measures design. There were two factors: platform type (VR and conventional monitor) and time perception mode (prospective and retrospective perception). Results showed that estimates made prospectively were significantly more accurate than those made retrospectively. There was no significant difference found between platform type, and there was no significant factor interaction. The findings are commensurate with previous studies of VR chronoception-distortion, which have prioritised the head-mounted display (HMD) VR technology and found time distortion effects with no difference in platform type. A tentative conclusion is that the aspect of VR responsible for the time distortion effects is more likely to be the immersive content and/or control mechanisms of the VR experience than the HMD technology.

Declaration.

This MScR Psychology Dissertation is the product of my own work and does not infringe the ethical principles set out in the University's Handbook for Research Ethics.
In submitting this dissertation, I agree that it may be made available for reference via any and all media by any and all means now known or developed in the future at the discretion of the University.
Signed

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September 2024

DOI: 10.46289/QPWP3937

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Acknowledgements.

I am very grateful for the support of Dr. Kerry Rees and Dr. Kim Schenke, whose combined input has been invaluable in helping me to undertake and complete this project, and for their confidence in me that I would be able to develop within this discipline from a standing start. I am grateful to various colleagues; my former Head of School, Anne Dawson, who provided me with this opportunity, Dr Matthew Lovett who has always been so generous with ideas, time, and support, and my Digital Media colleagues Stefhan Caddick and Dr. Suzanne Kobeisse, who have supported me with this project during a difficult time for us all.

Special thanks are due to my parents, Janette and Dave, who have always supported my various endeavours.

Finally, I wish to thank my partner, Emma Holloway, and my daughter, Elanor Dalby, without whose tireless support this project would not have happened.

Chapter One. Introduction.

1.1. Time Compression and Virtual Reality

Time is subjective. The mechanised reproduction of time afforded by clocks may provide a sense of temporal objectivity, but 'clock time' is fluid and subject to the variances of relativity, being affected by factors such as speed, gravity, and scale of perception (Rovelli, 2017). Two synchronised clocks will continuously diverge if one is placed on a table and the other on the floor due to being at different heights, an effect that will be visible after a duration dictated by the precision of the clocks (i.e. the more precise the clocks, the sooner the effect will be visible).

Similarly, the human experience of perceived time is one of fluidity and dependence on circumstances. When a sense of duration or temporal relationship between events seems fundamentally altered in comparison to an individual's perception, they experience 'time distortion' (Blom, 2021). The experience of time perception as replete with distortions is normalised to the extent that aphorisms such as 'time flies when you are having fun' are common in many cultures (Buonomano, 2017). Such normalisation also extends to experiences that are not commonplace; for instance, the reported phenomenon of time seemingly 'slowing' and even 'standing still' during traumatic experiences is widely known and accepted, even by individuals who have never experienced it (Campbell & Bryant, 2007). Despite the normalisation of such experiences, to date attempts to study the psychological phenomena of time distortion experiences - while numerous and varied - have also produced mixed results in test conditions.

Distortions in time perception are of contemporary interest due to societal interdependencies with ubiquitous digital technologies (Elwell, 2014) such as smartphones and social media platforms, because time distortion effects have been associated with various forms of digital media and technologies. Simple online (digital) stimuli – such as those associated with the social media platform *Facebook* (Meta Platforms Inc.) – have been shown to cause time distortion experiences (Gonidis & Sharma, 2017) due to effects on attention and arousal mechanisms. Time distortion has also been proposed as a reliable marker for social media addiction (Turel et al., 2018) as underestimations of duration were associated with users at risk of impulse control disorders when using social media compared to a control group, and disordered time perception predicted users' at-risk potential with a higher specificity (86.21%) than an established comparison method (40.48%).

Use of digital hardware has also been associated with time distortion effects in a variety of contexts. Andrews et al. (2015) found that user self-estimates of smartphone use during a single day (both duration and number of uses) were typically half of actual recorded use. Borges et al. (2015) found that digital display screens in public places reduced estimations of duration for disagreeable activities (such as queuing) and correspondingly improved customer satisfaction. One of the most studied areas of association between time distortion and digital media is computer gameplay, where Wood et al. (2007) found that 99% of gamers have experienced some form of 'time loss', and of these 67.5% considered it as sometimes or always a 'bad thing'. Time distortion has been associated with disordered gaming (Nuyens et al., 2020) which in turn has been shown to affect psychosocial wellbeing, and potentially interfere with various aspects of professional and personal life (Griffiths et al., 2012).

A common form of time distortion often associated with digital technologies is 'time compression', which can be defined as the phenomenon in which an individual perceives the duration of a given interval as being shorter than its timed duration (Mullen & Davidenko, 2021). This is often associated with the individual's attention being focused on a specific task, meaning that less attention is paid either to temporal processing when estimating an interval's duration (Block & Zakay, 1997), or to temporal cues or *zeitgebers* (literally 'timegivers'; Schatzschneider, 2016), such as the position of the sun, which provide indicators of time passing. This experience has been associated with various tasks and goals, and may be as simple as the sensation of 'losing track of time' when absorbed in a novel or film (Droit-Volet et al., 2011; Kovarski et al., 2022), or more specific, such as the experience of time becoming heavily 'compressed' into a shorter duration while in a virtual reality (VR) experience (Mullen & Davidenko, 2021).

Since the development of commercially available VR technology in the 1980s, anecdotal reporting of time compression has been relatively commonplace (Miller, 2016, Lanier, 2017). The phenomenon has been suggested to have potentially substantial effects, such as users feeling that only 15 minutes have elapsed after spending an hour in VR (Miller, 2016). To date, investigative studies of the phenomenon have been limited in number, often varied in approach, and have returned largely inconclusive results in lab test conditions. For example, various studies have found time distortion effects using different time perception paradigms (Mullen, 2023; Rutrecht et al., 2021; Schatzschneider et al., 2016; Unruh et al., 2021; Van der Ham, 2019), but have found little or no evidence linking the results specifically to VR in comparison with other technologies. While the phenomenon is not yet clearly understood and is the subject of ongoing research, reproduction of time compression effects in VR has been sufficiently reliable to allow the phenomenon to be employed with consistency in various applications. One of the most notable has been in medical distraction therapies (Miller et al., 1992) where virtual reality interventions are provided during medical treatments to distract the patient with the aim of reducing pain and anxiety during procedures (Indovina et al., 2018). Various studies have shown that patients undergoing medical distraction therapies can underestimate their duration, which has been associated with some perceived alleviation of symptoms (Loreto-Quijada et al., 2014), such as VR inducing time underestimation in chemotherapy patients (Chirico et al., 2016). Schneider et al. (2011) found that VR can make symptoms more tolerable depending on illness type, as women with breast cancer were more likely to experience altered time perception in VR than patients with lung cancer. While these results are promising in that experiencing VR during medical procedures elicits time compression in some instances, the causes of the phenomenon are not sufficiently well-understood. Additionally, because many studies did not compare their findings with other (non-VR) forms of digital media, there is currently insufficient evidence to demonstrate whether the time distortion effects employed during treatments are unique to VR.

It is as-yet unclear whether VR produces commensurate time distortion effects to other forms of digital media. As a relatively niche technology compared to conventional computer gaming or the use of social media platforms, time distortion effects from VR may have somewhat lower societal relevance compared to time distortions associated with use of those (and similar) digital technologies. As the 'Immersive Technologies' sector (which includes VR) continues to expand – globally the sector's estimated financial worth of $59.96bn in 2022 is predicted to follow a compound annual growth rate of 27.5% from 2023 to 2030 (GVR, 2023) - the phenomenon requires further understanding. Additionally, while time compression effects may be perceived negatively by recreational users, and may also be associated with psychosocial outcomes such as disordered gaming and social media addiction, it is also important to identify and understand the phenomenon for use in areas where it *is* required, such as in medical therapies.

1.2. Time Perception

Chronoception, the subjective experience of time, is quite distinct from 'clock time', the mechanised reproduction of time increments. Discussion of human temporal experience is complex and can be affected by implicit assumptions about the very nature of time itself (Rovelli, 2017), as well as by language and context (Buonomano, 2017). Studies may refer to different principles of time perception including simultaneity, successiveness, temporal order, duration, or temporal perspective, and may do so interchangeably (Block & Zakay, 1997). Typically, studies of chronoception tend to concentrate on perceptions of duration, although because the language of time perception has not been employed consistently by researchers, other areas of temporal experience may also be included or implied within studies. Additionally, human lack of a specific physiological time-sensing mechanism may be partly responsible for the way cultures across the globe tend to refer to time with metaphors drawn from other senses (Buonomano, 2017), as we may experience a *short* meeting, *look forward* to a holiday, or consider the *distant* past. An increasing body of neuroscientific research points toward interoceptive perception of bodily states, and specifically the insula cortex of the brain responsible for managing these body signals, as generating a sense of subjective time from an awareness of changing body states (Mondok & Weiner, 2023; Naghibi et al., 2024). This process is an interplay of complex factors in comparison to more specific senses such as tactile or olfactory processes which respond to particular stimuli, and consequently emphasises again the tendency to describe temporal experiences with reference to other, more tangible, sensations (Wittmann, 2023).

Complexities in verbalising the experience of time is of importance because time distortion effects may or may not be apparent to affected individuals depending on circumstances, a distinction often not captured accurately in language. Blom et al. (2021) found that in some cases, such as time slowing due to intoxication, or time 'reversing' or becoming 'circular' related to psychosis, the affected individual was often aware that their experience of time was distorted, while in other cases the distortion was not directly perceptible to the individual. Users of digital technologies, such as gaming (Nuyens et al, 2020) and VR (Mullen & Davidenko, 2021) experiencing time compression may not actively perceive a change in time passing. Chemotherapy patients experiencing VR distraction therapy, for example, do not appear to perceive time 'accelerating' during their treatment, although this may be suggested by the language employed to describe the effect. Instead, the experience of VR time distortion seems to be that the perceived 'VR time' feels natural and consistent to the user, while it is the external 'clock time' which appears distorted, and this only becomes apparent when an estimate of an interval's duration is shown to be inconsistent with the interval's recorded 'clock time'.

Such experiences accord with 'Vierordt's Law' (1868, as cited in Lejeune & Wearden, 2009) concerning judgements of duration; the observation that short durations are typically overestimated (perceived to be longer than they are) while long durations are typically underestimated. Implicit in studies relating to Vierordt's Law is that participants are not aware that their estimates vary from the actual 'clock time', and do not experience any perceptible time distortion. While the terms 'short' and 'long' durations have not been interpreted with consistency by researchers, a body of empirical study has supported Vierordt's Law (Roy & Christenfled, 2008; Yarmey, 2000). Conversely, Glasauer and Shi (2021) used modern research instruments to simulate Vierordt's findings, demonstrating that they may have been influenced by an unnatural research protocol related to the sequencing of experimental factors. While this may suggest that Vierordt's Law should be considered less as a specific metric and more as a general 'rule of thumb', it remains a rule of thumb which has empirical support and continues to be employed in contemporary research (Mallam et al., 2020).

1.3. Affective States

As time is subjective, affective states are influential in the perception of duration, and may also be associated with perceived chronoception distortions. Phenomena such as time appearing to 'accelerate' or 'fly' when engaged in an absorbing or appealing activity, and appearing to ‘slow down’ or ‘drag’ when engaged in an activity which is boring or disagreeable, are commonplace (Buonomano, 2017). Affective states including arousal, valence, and motivation, are necessary for consideration in studies of duration, as all have been found to affect time perception in various ways.

Arousal concerns the activation of the sympathetic nervous system (Storbeck & Clore, 2008), part of the autonomic nervous system which regulates bodily functions such as heart rate and digestion. The sympathetic nervous system is primarily associated with the so-called fight-or-flight response to stressors (LeWine, 2024) and contributes to physiological processes such as body temperature and cardiac output. Consequently, arousal can only be defined when an emotional state is brought to conscious attention and verbalised, such as the experience of being consciously ‘energised’ or ‘calm’ (Russell & Barrett, 1999). High levels of arousal have been shown to affect time perception by producing longer estimations of duration compared to neutral and low arousal states (Gil & Droit-Volet, 2012). Valence, meanwhile, is the subjective assessment of an affective state, such as ‘negative’ or ‘positive’ (Harmon-Jones et al., 2011) to the extent that all emotions have a positive or negative value (Chang et al., 2017). States of positive valence have been shown to produce underestimations of duration (Noulhiane et al., 2007) while negative valence states have been associated with longer duration estimations (Grommet et al., 2011). Accordingly, stimuli associated with high levels of arousal and negative valence might be anticipated to produce longer estimations of duration than positive, low-arousal stimuli. This is not always the case, however, as both arousal and valence can be affected variously by motivational states.

Motivation is related to action tendencies, such as approach motivation (the drive which directs behaviour toward a particular goal or outcome, Omorede, 2014) or withdrawal motivation (the drive to withdraw from a negative stimulus, Gable & Harmon-Jones, 2013). Motivational states have been associated with altering the effect of other affective states, such as arousal and valence, on time perception (Gable, Wilhelm, & Poole, 2022). Approach motivations in both positive and negative affective states have been shown to reduce estimation duration due to time ‘speeding up’ (Gable et al., 2016, Benau & Atchley, 2020), and withdrawal motivations have been associated with time ‘slowing’ (Gable et al., 2016, Matsuda et al., 2020). Individual differences can also influence time perception. Individuals with a propensity to strong emotional response seem to estimate time differently, as Liu and Li (2024) found that high state anxious individuals return longer estimates of duration than low state anxiousness individuals. Meanwhile, strong emotional regulation appears to limit the effect of time distortion caused by emotional states to only negligible levels (Tian et al., 2018).

1.4. Modes of Time Perception

Time perception research has been approached inconsistently to-date, as factors including language and implicit time-related principles have contributed to variations in study designs. One of the main areas of variance in chronoception research is the time perception mode employed, as study designs have typically examined single perception modes in isolation. Two separate time perception modes – prospective and retrospective - are employed when forming judgements of interval duration (James, 1890, as cited in Block & Zakay, 1997), and prior studies have typically focused on one or other of these.

Prospective estimates of duration are those undertaken when time is a known factor, and consequently prospective judgements are about a future experienced duration (Block, 1990, 1992). A person estimating a prospective duration has a clear starting point to begin their estimate ($t = 0$) and can allocate attentional resources to temporal processing to aid judgement of the duration. Retrospective processes are those undertaken when time is *not* known to be important during an interval, and the estimation of a particular interval’s duration only occurs after the interval has ended. Retrospective estimates are consequently related to remembered past events (Block & Reed, 1978). A person undertaking a retrospective estimation has no starting point for their estimate of commensurate precision to '$t = 0$' and cannot retrospectively allocate attentional resources to temporal processing. As-such, retrospective estimates are commonly thought to be based on memories accumulated during a given interval.

Attention and memory consequently form the basis of the theoretical models commonly employed in analysing both prospective and retrospective processes. Attentional models of prospective perception typically posit the conceptual idea of an internal pacemaker which produces 'pulses'. The Scalar Expectancy Theory (SET) model (Gibbon et al., 1984) proposes that these pulses operate like the 'ticks' of a clock. Once a stimulus which indicates the beginning of a timed interval is received, a 'switch' is closed whereupon pulses enter an 'accumulator'. Elapsed time is represented by the number of accumulated pulses, and this value is continually transmitted to working memory. The key aspect of the SET model is the addition of a 'comparator' which compares accumulated time stored in working memory to expected time stored in reference memory, and the consequent decisions which are made by this comparison. Alternatively, the Attentional Gate model (Block & Zakay, 1996, 1997) suggests that the frequency of pulses is a function of arousal, with pulse rates increasing or decreasing as arousal levels rise and fall. Pulses pass through an 'attentional gate' which becomes 'wider' with more attention paid to time and temporal processing, and 'narrower' as attention is allocated elsewhere. The wider the attentional gate, the more pulses proceed to working memory, resulting in longer estimations of duration, while a 'narrow gate' results in fewer pulses and shorter duration estimates. The Contextual Change model (Block & Reed, 1978), by contrast, posits that retrospective time is estimated in accordance with memories formed during a given interval. Consequently, a greater number and variety of memories to draw upon will result in longer perceived duration, and correspondingly longer estimations.

Prospective and retrospective perception are thought to be subserved by separate processes (Block, 1992; Hicks et al., 1976; Namboordiri & Stuber, 2021; Zakay & Block, 2004) which respond differently to variations in stimulus and circumstance. In prospective judgments, attentional resources are allocated between stimulus and processing of temporal information (Thomas & Weaver, 1975) with the result that increased allocation of attention to a particular stimulus or increased cognitive load (the amount of information that working memory can process at any given time; Sweller, 2011) produces shorter prospective estimations as less attention is allocated to temporal processing. Prospective duration estimates increase with simpler and/or smaller numbers of stimuli, stimuli which do not require the participant to react/interact, and without the need to divide attention between different stimuli (Block & Zakay, 1997). Cognitive load does not appear to affect retrospective perception in the same way, although retrospective estimates are affected by the information accumulated during an interval. Retrospective estimates increase with greater amounts of stored and retrieved information (Ornstein, 1969), number of recorded changes (Fraisse, 1963) or amount of demarcation and variation between events during an interval (Poynter, 1983). Specific attention to time does not seem to affect retrospective processing, except for situations where feelings (such as boredom) may produce a sense of time as contributing to a particular emotional state (Doob, 1971).

Variations in the modes of time perception have resulted in separate paradigms of study (Block & Zakay, 1997). Studies of prospective time perception, also referred to as 'experienced duration' (Block, 1990), typically employ what is known as the *prospective paradigm*; a test of a participant's capacity to judge a known time interval from the specific starting point of '$t = 0$'. A common process is to use an interval production method (Zakay,

1993) in which a participant stops a task when they determine that a set duration has elapsed, thereby generating a measurable interval which can be compared with the set time. Conversely, studies of retrospective time perception, or 'remembered duration' (Block, 1990), normally employ the *retrospective paradigm* which examines the capacity to judge a time interval only after it has elapsed, without being aware of the need to do so beforehand. Typically, a participant is asked to undertake a task and is subsequently asked to judge the length of the task interval. The retrospective paradigm will compare the target interval with the participant's (usually verbal or written) estimation. Studies of prospective perception are generally regarded as being more rigorous than those of retrospective perception, because a participant's timed estimation can be directly compared with the target interval (Mullen & Davidenko, 2021). In comparison, retrospective perception judgements may be subject to rounding biases (Huttenlocher et al., 1990) due to reliance on verbal or written estimates. Despite this, retrospective studies are numerous, and both time perception modes benefit from extensive bodies of research.

While estimates may be affected by a variety of factors including Vierordt's Law and affective states, in general prospective and retrospective perception have both been shown to be prone to underestimations (Block & Zakay, 1997) with prospective estimates being both longer (and hence more accurate) and more consistent than retrospective estimates. Many studies have examined intervals of less than 2 minutes, and some studies employing longer intervals of over 8 minutes have recorded overestimations in both perception modes (Walker et al., 2021). Studies employing both paradigms are not commonplace, so that comparison between the two modes can be challenging, and where studies have employed both paradigms, results have varied. Brown's (1985) study contributed to Block and Zakay's meta-analysis (1997) finding that both prospective and retrospective judgements became progressively shorter with increased non-temporal task demands. Conversely, Walker et al.

(2021) examined participants' time perception with high and low levels of cognitive load over two separate durations (an eight-minute task and a 58-minute task) in both prospective and retrospective paradigms. The study found significant overestimation of the eight-minute task by more than 33% in both perception modes, and underestimation of the 58-minute task, which broadly supports the principle of Vierordt's Law. However, while there were no differences between time perception mode in the underestimation of the 58-minute task, prospective judgements of the eight-minute task were significantly longer than retrospective judgements (and consequently less accurate). This partially supports Block and Zakay's Attentional-Gate Model, as prospective judgements were longer than retrospective judgements on average. Both averages were overestimations in contrast to Block and Zakay's findings, which were based predominantly on studies with shorter interval durations. Finally, cognitive load was not found to affect either time perception mode, the study's authors suggesting that this may have been mitigated by the duration of the tasks.

Of importance to studies of chronoception in both time perception modes is the nature of any stimulus involved in the perceived interval. The magnitude of a given stimulus has often been positively associated with perceived duration (i.e. the stronger a stimulus, the longer it appears to last; Goldstone et al., 1978; Fraisse, 1984; Xuan et al., 2007). Matthews et al. (2011) also found that the dynamic range (the logarithmic ratio between the largest and smallest values) of a stimulus, such as the magnitude of a visual stimulus compared to a backdrop, or a specific sound compared to background noise, may affect time perception more than level of magnitude. A visual stimulus with a low level of magnitude but clear contrast with a background, for example, will likely be perceived as lasting longer than a visual stimulus with a high level of magnitude and only a subtle contrast to a backdrop. The novelty of the stimulus may also affect chronoception, as the perception of new and novel stimuli is that they seem to last longer than familiar and repeated stimuli (Matthews and

Gheorghiu, 2016). Similarly, stimuli which produce emotional responses have been shown to affect both time perception modes. Increased emotional states have resulted in corresponding overestimations in both prospective and retrospective processes (Bisson et al., 2009; Cassidy & Macdonald, 2010) although conversely, tests of time perception and specific emotional stimuli and responses, such as positivity (Gable & Poole, 2012) and fear and excitement (Campbell & Bryant, 2007) produced underestimations.

Analysis of data from prospective and retrospective paradigms also produces variations. Retrospective judgements directly correspond to the experience of an individual, and an overestimation of interval duration indicates the individual has overestimated the interval in question. However, prospective judgements are inversely proportional to the individual experience. A timed overestimation of interval duration equates to a perceived underestimation of experience, as it illustrates that the individual believed they spent less time in the interval than they actually did. Consequently, care must be taken when interpreting data from studies employing different time perception modes (Cote, 2021).

1.5. Virtual Reality

Virtual reality (VR) as we understand it today originated in the 1980s with the first commercially available technologies, and popularisation of the 'virtual reality' term by VPL Labs (Lanier, 2017). Since then, VR has spearheaded a sector of technologies variously known as Extended Reality (XR) and (more recently) Spatial Computing, all of which fall under the broader category of 'Immersive Technologies'. A key characteristic of these technologies is that they involve some form of digital sensory displacement for a user, to produce what are often termed *immersive experiences*. Immersion in this context can be defined as the response to a specific and realistic mediated experience (Rózsa et al., 2022) or of being deeply engaged in an artificial world or circumstance 'as though it is real' (Coomans

& Timmermans, 1997). Immersive experiences can range from the relatively simple mediation and replication of real-world experiences in increasingly high fidelity and presence, such as binaural audio recordings, to the production of entirely artificial virtual 'worlds' found in immersive, open-world gaming.

Immersive technologies can be positioned on the Reality-Virtuality (RV) continuum (Milgram & Kishino, 1994; Skarbez et al., 2021) which progresses from physical 'reality' through increasing levels of digital displacement and 'virtuality' as the blending of real and virtual stimuli becomes more weighted toward virtual content. The blending of real and virtual stimuli together uses Augmented and Mixed Reality technologies to progress from Augmented Reality (real-world experiences with added virtual aspects, such as the use of face-altering filters on social media platforms) to Augmented Virtuality (primarily virtual experiences with some real-world aspects, such as the ability to see and interact with photorealistic avatars or metahumans of real-world users in virtual environments). At the opposite end of the continuum from *reality* are deep-immersion 'hyperreal' experiences such as virtual reality, in which at least one sense (sight) is completely separated from the world around the user, and replaced with a digitally constructed environment. In VR, this is normally achieved through the user wearing a head-mounted display (HMD); a box-like device worn over the eyes which contains screens (one per eye, to replicate a parallax effect). This means that the user can focus entirely on the virtual experience while separated from real world stimuli. In most cases the user can turn their head to view more of an experience, often in 360 degrees (vertical and horizontal), with the aim of the user feeling centred in, and surrounded by, a digital environment.

Traditionally VR technologies were rare, expensive, and technologically prohibitive, as users needed additional expensive computing technology to support the VR platform. They also had limited applications for home use, being primarily associated with industrial contexts such as training platforms (Bogon et al., 2023). However, as the technology has improved and become more affordable in recent years, the main growth in the sector appears to be driven by increased numbers of recreational home users. This is suggested by the sale of new commercially available ‘standalone’ HMD units which feature on-board processing and do not necessarily need to be connected to a computer. These units accounted for 61.9% of the global immersive market in 2022 (GVR, 2023). While a developing body of research suggests that VR has the potential to be highly addictive (Barreda-Ángeles & Hartmann, 2022; see also Huddleston, 2022; Kaimara et al., 2022; Noone, 2022), even amongst regular users average VR engagement seems to be much lower than conventional gaming in terms of time spent on the activity. Various informal studies suggest that many home VR users currently engage with the technology relatively infrequently - typically 2-4 times per week, and usually for around 30-45 minutes at a time (NRG, 2022) - which is low compared to the average 112.8 daily minutes US (non-VR) gamers aged 15 to 19 played in 2020 (Statista, 2023). However, as the sector expands and commercial VR content improves in both immersive quality and longer-form application, average use is likely to increase. Additionally, the current trajectory for computing technology more generally is toward so-called Web 3.0 and Spatial Computing platforms such as Apple’s *Vision Pro* HMD device (Apple Inc., 2024), which offer new methods of blending real and virtual stimuli. In this environment, understanding and identifying potential time distortion associated with immersive devices and content becomes of increasing value and importance.

1.6. VR Components and Types

VR experiences typically comprise three separate components: the HMD (head-mounted display unit), the immersive content being experienced/interacted with (the digital environment), and the control mechanisms for any interaction within the experience. The ‘virtual reality’ term has been used inconsistently by researchers, with some studies differentiating ‘VR HMD’ (VR using head-mounted display technology) as a sub-category of broader virtual reality experiences (Kaplan-Rakowski & Gruber, 2019; Mallam et al., 2020). Some studies have also incorrectly described the HMD as ‘head-mounted *device*’ rather than ‘head-mounted display’ which may lead to confusion with other head-mounted technologies. Because immersive non-HMD experiences are also referred to elsewhere as different types of (non-VR) experience (e.g. ‘first-person shooter’ games or ‘Web 3.0/metaverse’ experiences), for clarity and in-accordance with industry norms, the current study will proceed with the definition that contemporary VR must always include some form of HMD device. Digital environments and immersive technologies which do not include an HMD will be referred to differently on a case-by-case basis. Similarly, the digital environments of immersive experiences are often referred to as ‘virtual environments’. Technically, however, a virtual environment is a collaborative digital space allowing users to interact with each other, and with various digital tools. While such environments can be accessed using VR technologies, for clarity this study will refer to the immersive content typically used by VR systems as a *digital environment*. Additionally, VR systems often employ immersive control mechanisms to allow the user to interact with the digital experience. While some contemporary technologies track the user’s actual hands without the need for controllers, more typically VR systems use two hand-held controllers, one per hand, which are tracked in three-dimensional space by the HMD to provide a commensurate experience of the user’s hands while in VR. Such single-hand controllers are dissimilar to conventional computer interfaces such as a game-controllers (where both hands hold and operate the same device, the position of which does not normally affect the experience) or a mouse and keyboard. While VR controllers do not have a specific technical term to-date, this study will refer to VR-specific controllers as ‘tangible controllers’, based on the principles of ‘Tangible User Interfaces’ (TUIs; Ullmer & Ishii, 1997) and ‘Tangible Gesture Interaction’ (Hoven & Mazalek, 2011).

VR experiences can be broadly categorised as either ‘static’ (Read et al., 2021), ‘3DoF’ (‘three degrees of freedom’), or ‘6DoF’ (‘six degrees of freedom’; Mechatech, no date). In static experiences, the user’s position and point of focus are both fixed, making only limited use of the immersive capabilities of the technology. If included, such experiences allow only basic interaction with a digital environment by using non-tangible (hand-to-object) controllers, such as a computer keyboard and mouse, or games console controller, which do not replicate the sense of the user’s own separate hands within the experience. Examples include watching a film in VR, where a full-size cinema screen can be created inside the HMD (van der Ham, 2019), or playing a basic fixed-position game which does not actively make use of the rotational axes and tangible interaction of the technology (Mullen & Davidenko, 2021). 3DoF experiences are designed around rotational axes, allowing (and usually encouraging) the user to look in all directions, and may allow interaction with an environment by replicating the sensation of ‘hands’ (either by using tangible controllers or by scanning of the user’s own hands) but do not allow the user to move around inside the experience. Examples include VR documentaries such as *On The Morning You Wake (To The End Of The World)* (Colinart et al., 2022) and fixed-position games such as *Beat Sabre* (Beat Games, 2018). Objects always remain a fixed distance from the user in 3DoF experiences, independently of user movement. 6DoF experiences employ rotational and transitional axes, allowing the user to receive visual stimuli from all directions, interact with the environment using tangible technologies, and additionally include the ability to move around within the digital environment, either by physically moving (e.g. walking) or by using controllers.

Each category of experience offers the potential for different levels of immersion, as taxonomised by Milgram and Kishino (1994) and subsequently updated by Skarbez et al.

(2021), by using the reality-virtuality (RV) continuum above, and employing three taxonomic dimensions: Extent of world knowledge (how detailed and extensive the digital environment is), reproduction fidelity (how real an experience seems based on technological clarity), and extent of presence metaphor (the level to which the user feels that they have been 'transported' away from reality and into the experience). All immersive (XR/spatial) technologies can be positioned on the RV continuum, and as the technology which provides exclusively virtual experiences (compared with mixed, augmented, and spatial technologies which blend real and digital stimuli), VR represents the deepest level of displacement into a digital environment currently (technologically) available and, as discussed earlier, is consequently positioned at the opposite end of the continuum from 'reality'.

1.7. Immersion

One of the main aims associated with VR technologies is to provide users with immersive experiences. The difficulty in discussing immersive experiences is that a clear and consensual definition of 'immersion' has yet to be found. This is partially due to its interdisciplinary nature, because immersion might equally refer to a state of absorption in a novel as to hyperreal displacement in a multisensory VR experience. While immersion relating to digital experiences has been thought to be a state of mind reflecting how *present* a user believes themselves to be within a virtual environment (Witmer & Singer, 1998), a broader consensus among researchers is that 'immersion' and 'presence' are separate concepts. As such, immersion in this context is an objective and measurable characteristic of a digital environment (Bystrom et al., 1999) while presence is the extent to which a user believes themselves to have been displaced or transplanted *into* a digital environment (Nash et al., 2000; Lemmens et al., 2022).

One of the key aspects of VR immersion is how believable an experience is (Frost et al., 2022), and fundamental to believability is the perceived realism it provides (Wilson & Soranzo, 2015). Research into VR realism is ongoing, and it does not appear to be necessarily related to the sophistication and reproduction fidelity of the visual experience (Huang & Klippel, 2020; Weinrich et al., 2021). Informal reviews and forums relating to clearly non-real content such as the 'cartoon' environments of online VR metaverse *Meta Horizon Worlds* (Meta Platforms, Inc.) and the (sometimes) low-resolution environments of VR social platform *VRChat* (vrchat.com) still suggest broadly positive experiences of realism. Instead, current research suggests that there is something inherent in the experience of 'being inside' an HMD which provides some form of equivalent - and even 'enhanced' - realism. For instance, Renganayagalu et al. (2019) found HMD users reported higher levels of immersion and realism than non-HMD users, which resulted in an increased motivation to use the VR technology.

Similarly, immersion has been categorised by Kaplan-Rakowski and Gruber (2019) as relating to 'Low' and 'High' level technologies. Low immersion refers to immersive content viewed on standard equipment, such as conventional monitors, while high immersion refers to immersive content experienced on HMD-style platforms. The proposed area of differentiation is 'spatial realism', with the HMD technology seeming to produce a more spatially realistic experience for the user. Lemmens et al. (2022) found a strong sense of spatial presence when comparing VR gamers with gamers using the same content in a non-VR context. This mediated the effectiveness of the game content on players' emotional responses, as VR players returned higher levels of fear and hostility in survival horror games compared to conventional monitor users. The study also found variations in heart rate variability, suggesting a correlation between VR use and physiological arousal, although the researchers noted it is unclear whether emotionally relevant stimuli would make a VR environment more appealing, leading to an increase in presence and subsequently arousal (Diemer et al., 2015), or whether arousal in VR would lead to alertness, and a corresponding increase in presence (Freeman et al., 2005). Zhang et al. (2022) found that altering spatial perspectives and size ratios for users in VR produced differences in environment perception, specifically related to the perception of environmental hazards and the risks they pose, suggesting that it may not be solely spatial realism per-se which produces heightened immersion levels in VR.

While research into immersion and presence is ongoing, the consensus amongst both VR content and technology producers, and amongst VR users, is that there is something inherently *immersive* about VR technology and its correlates/derivatives in XR and Spatial Computing, hence the umbrella term 'immersive technologies'. The present research will consequently conform to the contemporary principle that immersion refers to something objectively measurable about an experience, while presence refers to the level of 'transportation' into an immersive environment that a user may experience (Lemmens at al., 2022).

1.8. Flow States

One of the most commonly studied areas of digital media-related time distortion is conventional (non-VR) gaming, and the commensurate experience of 'time loss' (Wood et al., 2007; Nuyens et al., 2020). A common theory in conventional gaming relating to time loss concerns self-awareness, and the associated connection with so-called 'flow states' (Csíkszentmihályi, 1975) in which an individual becomes completely involved in a task which matches their skill level to an equivalent level of challenge, such as may be found in gaming. Csíkszentmihályi (1993) suggests that a flow state comprises four main components (control, attention, curiosity, and interest) and eight elements (clear goals with immediate feedback, reward, a liminal balance between skills and challenge, a merging of awareness and action, concentration, sense of control, loss of self-consciousness, and time distortion). An individual experiencing a flow state is likely to be concentrating attentional resources on the task in hand, to the extent of experiencing potential loss of self-awareness for the interval of the task. An associated consequence of this may be an experience of distorted time perception whereby the individual in flow is prone to under or overestimate the duration of the experience. Zakay (2014) attempted to clarify this distortion effect by comparing flow states with boredom, finding that boredom leads to an overestimation of duration, and flow experience leads to an underestimation of duration. Consequently, varying degrees of flow state, sometimes called *gameflow,* are thought to be a key contributory factor in 'time loss' during gaming (Curran, 2013).

The principles of flow support models of prospective time perception such as 'SET' (Gibbon et al., 1984) and the 'Attentional Gate Model' (Block & Zakay, 1996, 1997) given that allocation of attentional resources toward an absorbing task and away from temporal processing produces shorter (and even 'lost') duration estimates in prospective perception. It may be more complicated to attribute time distortion from flow states to retrospective models, which are largely developed from memories accumulated during a given interval. Research into this field within VR is ongoing, notably Rutrecht et al., (2021) and Lemmens and von Münchhausen (2023). Flow states are achievable in VR and may therefore be equally connected to VR time compression, although initial research suggests that flow may occur differently in VR compared to normal gaming (Lemmens & von Münchhausen, 2023). This is partly due to the potential for perceived similarities between flow and immersion, which have even been thought to be sufficiently close as to make the concepts interchangeable (Michailidis et al., 2018). As discussed above, immersion is typically considered to be the perceived measurable and objective properties of a mediated environment (Lemmens et al.,

2022) and flow is a state of optimal performance within a sufficiently challenging and rewarding experience (Csíkszentmihályi, 1993). Even so, there may be aspects about the affordances of immersive environments which contribute to the development of a flow state, such that the point of equilibrium between challenge and reward may be different to conventional gaming. Lemmens and von Münchhausen (2023) found that users in VR did not experience boredom when a game experience was too easy, and when a game was excessively difficult VR users were prone to considerable levels of frustration. While the study did not compare matched content with users in a non-VR condition, the reported findings suggest that the equilibrium point between challenge and reward required for a flow state may be lower for VR users (closer to the 'easy' end of a challenge continuum) than in conventional gaming. This may have implications for time perception in VR, as it may be easier to enter into a flow state if a VR experience does not need a particularly high level of challenge for a flow state to be achieved. Given the time distortion associated with flow states, VR time compression may consequently be more associated with experiences offering only limited levels of challenge. Furthermore, the lack of boredom reported by Lemmens and von Münchhausen may suggest that a challenge element is not a prerequisite for flow states in VR.

A related concept to flow specific to digital technology is cognitive absorption, which can be defined as the state of a user's involvement with a particular technology (Zhang et al., 2006) or the extent of a user's absorption when engaging with a digital system (Palombo et al., 2024). Cognitive absorption is not unique to gaming or VR, and can consequently only provide generalised conclusions similar to Vierordt's Law in time perception. Nevertheless, it may be particularly relevant to VR, given the sensory displacement and tangible control mechanisms of the technology, which have been thought to heighten cognitive absorption (Palombo et al.). Agarwat and Karahanna (2000) identified five dimensions of cognitive absorption; temporal dissociation, focused immersion, heightened enjoyment, control, and curiosity. While flow states are a more specific cognitive state linked to activity and challenge, therefore, temporal dissociation may still be a feature of VR regardless of flow, based on the level of cognitive absorption experienced by users.

1.9. VR and Time Perception

To date, studies of time perception in virtual reality have been limited in number and have tended to be varied in approach so that their findings cannot be accurately compared. Common features of many studies include small sample sizes, custom immersive content which cannot be reproduced elsewhere, and the lack of a comparison with a matched non-VR condition, meaning that findings cannot be clearly attributed to the use of virtual reality specifically. Of those studies which have included matched conditions, few have found a significant effect, and in some studies where an effect has been found (Lugrin et al., 2019; Mullen & Davidenko, 2021), larger and more varied studies – Unruh et al. (2021) and Mullen (2023) respectively - have been unable to replicate the results.

Another common feature of VR time perception studies is that, of the three main variables of a VR experience (HMD, immersive content, and controllers), studies have typically focused on the HMD technology rather than the immersive content/experience, or the controllers used to interact with it. As-such, many studies have employed static experiences (as opposed to 3DoF and 6DoF) with the intention of using the HMD as an approximation of the way one might use a more conventional monitor/television screen, rather than as a device for immersive experiences specifically. This has been useful for comparing HMD and non-HMD conditions and attempting to separate the HMD from the immersive content and control mechanisms, in determining which variable may be most associated with VR chronoception-distortion. Van der Ham (2019) found no significant effect when comparing retrospective time perception in VR and non-VR users in a test which employed a static experience (participants were asked to estimate the duration of movie clips, viewed either in a real-life cinema or a virtual counterpart). Mullen and Davidenko (2021) found a significant time compression effect in VR when comparing prospective time perception in matched HMD and non-HMD conditions. Participants played a basic maze game using a non-VR games console controller, representing a static (rather than a 3Dof or 6DoF) experience. Mullen (2023) was unable to replicate these results in further, larger studies involving the same static 'maze' experience, which found inconclusive and oppositional effects. Analysis of the mixed results of static experience studies suggests that VR time distortion may not be associated with the display (HMD) technology specifically.

Schatzschneider et al. (2016) found that manipulation of zeitgebers, cognitive load, and immersion level, produced significant effects on prospective duration judgements in VR. Participants' time estimates were more accurate in a digital environment with a perceptibly moving virtual sun (zeitgeber) than a static sun, although both circumstances produced overestimations, while tasks which increased cognitive load produced underestimations. The study found no significant effect between matched VR and non-VR conditions, suggesting again that time distortion may be more associated with immersive content (the aspect of the study shared between conditions) than display type. Rutrecht et al. (2021) tested participants playing a game in VR and on a conventional screen while manipulating flow states, finding that participants in VR performed better and reported higher levels of presence than conventional screen users, but also finding no difference in flow states and associated time distortions between the two platforms. Unruh et al. (2021) found that users embodying an avatar (a virtual body) experienced a significantly faster perceived passage of time than non-avatar participants, in both VR and non-VR conditions, again illustrating a potential connection between time perception and immersive content, and/or control mechanism, rather than display technology. Alternatively, Bogon et al. (2023) found that VR does not actually affect the sense of time, but instead changes expectations about the duration of processes. The study compared timing performance in VR to real-world scenarios, and found that judgements of the duration of a physical process (a bottle of water being emptied) were affected by VR, while judgements of abstract units of time were unaffected. While this study examined short durations of up to around 8 seconds and employed a prospective paradigm, leading to some limited comparability with studies of retrospective perception and those examining longer duration experiences, this is still a key finding which requires further investigation.

Of the studies discussed above, few have examined VR time compression specifically. Further research is required in this area, as it may be that time compression occurs differently in VR compared to real-world situations. Time compression is the perception of an interval's duration as being shorter than its timed duration (Mullen & Davidenko, 2021) and the experience of this phenomenon, particularly the perception involved, may vary considerably in different contexts. The experience of 'time becoming lost' in conventional gaming (Nuyens et al., 2020) may differ from the experience of 'losing track of time' when immersed in a novel or film (Kovarski et al., 2022). Rather than time being 'lost' or 'lost track of', VR time compression appears to be associated with the experience of time being literally 'compressed' into a shorter duration, potentially due to experience acceleration. This has not been the specific subject of any known studies, and evidence is only anecdotal (see Appendices 10, 11, and 12 for examples of online discussions), although Bogon et al. (2023) is a related study due to the variances found between physical processes and abstract time units in VR. Complexities in verbalising time perception are also of consideration, as some users describe VR time as being accelerated (Appendix 12), while others suggest that time 'slows' in VR (Appendix 11), although this can be taken to mean that perception is slow compared to accelerated mechanics within an experience (Appendix 10). Taken together, such evidence suggests an impression amongst some users of an accelerated flow of time in VR, leading to events occurring more rapidly in VR than in real-world situations, and VR time becoming ‘compressed’ rather than ‘lost’. Whether this experience is perceptible to users as it occurs, or only retrospectively, is unclear. While no conclusions can be drawn until verified by research, it does appear to have been acknowledged to the extent that some VR experiences, such as *American Truck Simulator* (SCS Software) now include configuration settings whereby participants can adjust a time ‘warp’ feature (Appendix 10). These settings alter temporal game mechanics, such as the perceived speed of traffic light changes, to allow game time (VR ‘gameflow’) to occur at a more ‘natural’ speed based on individual preferences. This could be interpreted as a form of virtual ‘temporal mechanics’ (Jarvis, 2021), whereby a temporal experience in VR is determined from the holistic experience of the speed of perceived changes and events. Should such anecdotal evidence be verified by research, this may suggest that the experience of VR time compression relates more to the sensation that an experience has passed more quickly than it did, rather than the time of an experience becoming ‘lost’ in some way, as might be expected in the temporal dissociation of flow states and other phenomena. There are various aspects of VR technologies and experiences which may support such a conclusion, such as the technological sensory isolation involved in VR due to the HMD technology, and which will be developed further in different contexts below.

Given that reporting of VR time compression is often anecdotal, the inconclusive results from current studies could suggest that the phenomenon is not empirically reliable and may not even exist as a pattern of predictable experience across groups of users. The reliable employment of VR time compression in various contexts such as medical therapies would suggest otherwise, however, leading to the conclusion that there is something inherent to VR time compression which has yet to be identified, and which will render the phenomenon more consistent to test conditions. The inconclusiveness of current research findings indicates where this might be found. VR experiences consist of three main variables (HMD, content, and control mechanism) and since previous studies of chronoception in virtual reality have tended to concentrate on the HMD technology, and to-date have illustrated little evidence linking the HMD to time compression (and other chronoception-distortion effects), there is a clear need to investigate the content and controller variables more specifically. The inconsistent findings of HMD-specific studies suggest that time compression effects may be caused by all three variables acting in concert, or the immersive content of a VR experience and/or the tangible control mechanisms employed, rather than just the HMD specifically. For understanding of VR time compression to develop, therefore, further studies are required that do not concentrate on the HMD specifically, and which investigate the immersive content and tangible control mechanisms, as well as the ways in which the variables of the experience work in concert.

The immersive content employed by the majority of VR time perception studies to date has been custom-designed for the needs of the study. Likewise, the control mechanisms employed have been selected to operate with the custom content and have usually been generic technologies (e.g. games console controllers) which are not specific to VR. Given the capacity to control for and manipulate variables that custom content offers, its use in studies to-date has been beneficial in helping to identify that VR time distortion effects do not appear to be caused by the HMD specifically. At the same time, as the findings reported have not consistently replicated and identified the experience of VR time compression, studies employing commercially available content are also required. Only a small number of matched-content studies (Mallam et al., 2020; Rutrecht, 2021) have tested participants' time perception using commercially available content, and even these studies did not use content specifically created for VR. This is important, as VR-specific experiences are designed to be commercially successful, leading to an emphasis on aspects which may enhance (or be enhanced by) VR technologies. These include tangible interaction (e.g. virtual hands) using VR-specific controllers, and immersive experience design promoting high levels of arousal and valence (Estupiñán et al., 2014), which have often been absent from earlier studies. Lemmens at al. (2022) successfully employed commercially available matched content (although not specifically designed for VR) in VR/non-VR conditions to examine arousal and presence, and Lemmens and von Münchhausen (2023) used VR-specific content to examine flow states in VR (albeit without a matched-content condition), pointing the way for future research into VR time perception. Consequently, given the HMD-focused ('static' experience) designs of previous studies, and the tendency for studies to employ custom-content, with inconsistent results to-date from both approaches, there is a need for studies employing commercially available 3DoF or 6DoF content to determine whether these variables result in more reliable reproduction of VR time compression effects in test conditions.

Another characteristic of previous VR time perception studies has been the employment of a single time perception mode, examining either prospective or retrospective perception in VR. Each mode of perception is subserved by separate processes and as outlined above, there are corresponding variations in the modes and processes being studied as well as the research paradigms associated with them (Block & Zakay, 1997). Such variations have consequently made studies of VR time perception difficult to compare. Given the three existing variables of the VR experience (HMD/content/controllers) as well as subordinate variables including the use of commercial or custom content, and use of VR-specific or generic controllers, it is important for studies to illustrate effects in both time perception modes for clear comparison. This represents a novel methodology for studies of time perception (not just those specific to VR) as dual time perception modes are rarely employed within the same study. However, to isolate time compression effects to one-or-more of the three variables which are always present in VR experiences, it is necessary to determine the role played (if any) by specific time perception modes, by providing the means of direct comparison between them.

A final commonality of VR time perception studies is that the technology is often unfamiliar to participants, and consequently the novel aspects of VR can affect studies in various ways. As seen above, novel stimuli can be associated with longer duration estimates which could affect results and lead to overestimations. Additionally, the novelty of the technology can affect certain study designs. Mullen and Davidenko (2021) employed a counterbalanced (matched VR/non-VR) within-participants design, where participants were allocated to using either VR or a conventional monitor in one condition, and subsequently asked to switch platforms in a second, subsequent, condition. The researchers were compelled to disregard data from their second condition as it became clear that participants had experienced significant anchoring effects from their first condition which affected their time perception estimates. This was considered to be a consequence of the novelty value of the VR experience. Such considerations therefore suggest the use of between-participants designs for future studies.

Taken together, analysis of existing studies into VR time perception, and time distortion in-particular, suggests that subsequent studies of the phenomenon are required which employ VR-specific, high-immersion experiences in 6DoF format, and which make full use of tangible control mechanisms. These studies should include matched-content VR/non-VR groups to illustrate whether findings can be attributed to VR specifically, and should also employ both prospective and retrospective perception modes, as well as between-participants designs to avoid the potential for anchoring effects related to the novelty factor of

VR which have been found in earlier studies. Such studies would diverge considerably from the majority of previous studies of VR time perception, and based on current literature concerning general time perception might produce a number of divergent and interesting findings.

1.10. Study Considerations

For many VR users, a likely initial assumption is that the typical experience of time compression only occurs once a VR session is over, and specifically as a result of comparison with the actual 'clock time' elapsed during the interval (i.e. temporal judgement was not integral to their VR experience). Consequently, it follows that retrospective judgements in VR may be of primary concern in investigating the phenomenon of VR time compression. At the same time, judgements of known duration in VR (prospective perception) need to be tested to determine the extent to which the phenomenon is common to both modes of time perception. Because retrospective time perception is less accurate and more varied than prospective time perception (Block & Zakay, 1997), similar results would be anticipated in such studies, particularly if retrospective perception is indeed the time perception mode most commonly associated with VR time compression, which comparison between the two modes may help to illustrate.

The extent to which retrospective inaccuracy and variance would be affected by the VR experience is unclear. Nuyens et al. (2020) found that regular non-VR gamers exhibited more accurate prospective time perception and equivalent retrospective time perception to non-gamers in a neutral setting, but exhibited impaired retrospective perception resulting in time loss when aroused by gaming stimuli. As a VR-specific 6DoF experience is likely to produce at least commensurate, and potentially increased levels of immersion compared to conventional gaming, increased retrospective distortion may therefore be anticipated.

Furthermore, by comparing gamers with non-gamers and finding variances in time perception, Nuyens et al. suggests an additional variable, which is the prior experience of participants with the technology and content. It will be necessary, therefore, to ascertain the level of prior experience with VR for all participants in VR time compression studies in order to accurately analyse results, and to begin to determine whether similar discrepancies exist within VR.

The level of immersion afforded by commercially-available 6DoF VR experiences may also provide varying results compared to previous VR time perception studies, due to the principle of spatial realism associated with immersion outlined above. VR experiences have been shown to produce stronger spatially-realistic effects than non-VR experiences (Lemmens et al., 2022) which has been linked to higher levels of immersion. Human lack of specific time-sensing physiology has led to the use of spatial metaphors when discussing time, as outlined above, and Calabria et al. (2011) found that neurologically, mental representations of time could be linked to spatial representations and may even share some common cortical networks. The consequent emphasis placed on spatial realism by VR, particularly compared to that of digital environments in non-VR contexts as illustrated by Lemmens et al. may illustrate a specific and potentially unique aspect of VR and its effect on time perception.

Other factors affecting time perception may also be enhanced by high-immersion 6DoF VR. Cognitive load is known to affect time perception, and studies examining whether VR increases cognitive load have produced mixed results to-date. Armougum et al. (2019) found no difference between VR and non-VR participants in a cognitive load task, while Frederiksen et al. (2020) found that VR increased cognitive load while performing complex motor skill tasks, and Juliano et al. (2022) found that VR increased cognitive load related to explicit learning and long-term motor memory formation. As outlined above, cognitive load specifically affects prospective time perception, with higher levels of cognitive load resulting in shorter estimations as attentional resources are allocated away from temporal processing (Block & Zakay, 1997), and consequently if cognitive load is increased in VR, the expected result would be underestimations of a test interval duration. By contrast, cognitive load has not been shown to affect retrospective processing in the same way (Block & Reed, 1978) and cognitive load would therefore be unlikely to produce retrospective distortions in VR.

Retrospective perception models are memory-based, such as the Contextual Change Model (Block & Reed, 1978), and studies into the effect of VR experiences on memory again present a mixed picture. Some studies have found that VR and/or immersion in a digital environment compromises memory formation. Fox et al. (2009) found that viewing changes in participants' own virtual avatar limited the ability to recall numbers, with participants who reported higher levels of presence performing less effectively than those in a low-presence group. Lamers and Lanen (2021) found that undertaking a memorisation task in VR instead of a real environment lowers recall accuracy in a real environment by 24%. Others have found that VR enhances memory formation in various ways, including improved recall due to immersive presence (Bailey et al., 2012), improved spatial memory and cognitive skills (Cimadevilla et al., 2023), improved medium-term retention during training compared to a standard training video (Shen et al., 2021), and memories formed within an HMD compared to a conventional monitor condition (Krokos et al, 2019). As outlined above, the Contextual Change model posits that retrospective estimates increase with greater amount of stored and retrieved information (Ornstein, 1969), number of recorded changes (Fraisse, 1963) or amount of demarcation and variation between events during an interval (Poynter, 1983). Consequently, improved memory in VR would likely equate to longer retrospective duration estimates, while compromised VR memory would result in shorter retrospective estimates. Mallam et al. (2020) compared participants' time perception in matched VR/non-VR while undertaking a searching task within a commercially available digital environment. All participants exhibited a learning development, as each participant undertook three 'rounds' of the task, showing improvement each time due to remembered features, which was illustrated by decreasing time spent on task in each round. Non-VR participants exhibited a significant improvement in their search accuracy compared to VR, suggesting better memory formation in the non-VR condition, although all participants returned commensurate levels of overestimation compared to their actual search duration, regardless of condition.

A final consideration affecting VR time perception may be the stimulus afforded by the experience. As noted above, VR is still a somewhat unusual technology, and it is likely that many study participants will have limited or no experience using it, while even fewer are likely to be familiar with the specific content experience employed in any study. In addition to the findings of Nuyens et al. (2020) that regular non-VR gamers experienced compromised time perception compared to non-gamers when aroused by gaming stimuli, which suggests prior experience of VR may be a factor, the 6DoF experience itself may present an aspect of both intensity and novelty. For many participants, the novel aspects of the experience are likely to be both the unusual technology, and the unusual experience of being immersed in a digital environment, while the magnitude of the experience is likely to be enhanced by the hyperreal nature of the experience (Renganayagalu, 2019). This is important because, as seen above, novel stimuli seem to last longer than familiar and repeated stimuli (Matthews & Gheorghiu, 2016), and stimuli with high levels of magnitude or dynamic range are perceived as being longer than weaker and more subtle stimuli (Xuan et al., 2007; Matthews et al., 2011) which could affect studies of VR time perception. Consequently, participants' level of prior experience with VR will be used as a covariate in the current research.

Emotional response to the 6DoF experience is also an additional consideration. The relationship of affective states to time perception is of importance to studies in virtual reality, as VR has been shown to increase levels of arousal and valence in users compared to non-VR conditions (Estupiñán et al., 2014; Lemmens et al. 2022). VR has also been associated with increased motivation to use the technology (Renganayagalu et al., 2019) and motivational states have been associated with altering the effect of other affective states on time perception (Gable et al., 2022). While the effect of emotional responses to stimuli on time perception is complex, experiences which are associated with fear and trepidation have been shown to increase subjective time (Campbell & Bryant, 2007). The unfamiliar technology alone may cause some feelings of trepidation in some users (Hurler, 2021) while many 6DoF VR experiences are designed to heighten emotional response in destabilising ways. When combined with the novel and hyperreal aspects of the experience, this may indicate that overestimations of duration could be anticipated when testing time perception in VR-specific, 6DoF experiences, and particularly those with high levels of arousal.

1.11. Estimation Accuracy

As a consequence of these considerations, the current study will include a number of novel aspects. It will be the first known study to test VR time perception in both prospective and retrospective perception modes. It will also be one of only three studies known to have used a 6DoF immersive experience to examine time perception (Mallam et al., 2020; Rutrecht et al., 2021) and the only known study to employ commercially available content designed specifically for VR, making use of the full immersive capacities of the HMD and controller technologies. In attempting to begin to determine which variable or combination of the three main variables of a VR experience (HMD/Content/Controllers) is most associated with VR time compression, the study will compare participants in VR with participants using a conventional monitor, and because the study will employ VR-specific content, it will also be the first known study to test content designed specifically for VR in a non-VR condition.

Given that many of the variables discussed above require further research and understanding, the anticipated outcome from the current study is unclear, leading to a non-directional hypothesis. Given the novel aspects of key parts of the study, the addition of a clear and fixed point of comparison will be of use in analysing the data, and may provide more directionality to the hypothesis. In the current study, this point will be the accuracy of participant estimations in comparison to the target time.

In both prospective and retrospective paradigms discussed above, participants are asked to judge a set interval duration. In prospective studies the participant knows the target duration beforehand, while in retrospective studies the participant is only given the target duration retrospectively, and in both cases a comparison can be drawn between the estimate and the target duration. While the employment of both time perception modes already allows for a point of comparison, as estimates in both modes can be compared against one another, in order to determine which time perception mode is more distorted a ratio-level of measurement is required based on comparison with the target duration. Accordingly, the outcome of the present study will be based on the accuracy of participant estimates in both time perception modes (prospective and retrospective) and using either VR or conventional monitor technology.

By contrast, Mullen and Davidenko (2021) examined VR time compression in a prospective perception mode, and employed estimate-duration as the main dependent variable of their study, rather than a comparison between estimate and target duration. While Mullen himself was unable to replicate the study's findings in subsequent, and more extensive, further studies (2023) Mullen and Davidenko's experiment is one of the few matched-content (VR/non-VR) studies to demonstrate significant findings, as the researchers found that average estimates of a five-minute interval were 72.6 seconds longer in the VR condition than in the conventional monitor condition. The researchers interpreted this finding as supporting their hypothesis of increased time compression in VR. However, it is noteworthy that the VR estimation average was a 27.4-second overestimation of the 300 second (5 minute) target duration, while the average conventional monitor interval was an underestimation by 45.2 seconds. This suggests that VR estimation was actually more accurate than the conventional monitor estimation, indicating a greater degree of possible time *dilation* in the conventional monitor condition compared to time *compression* in VR, an effect which is only apparent when participant accuracy is analysed. Accordingly, accuracy of participant estimations of duration will constitute the main dependent variable in the current study.

1.12. Hypotheses

The dependent variable for the present research is the accuracy of interval estimates in comparison to a 510-second target duration. This is taken to reflect the perception of time experienced by study participants. The independent variables for the study are platform type (either VR or conventional monitor) and time perception mode (retrospective or prospective perception).

The null hypotheses are that there will be no significant differences in accuracy of duration estimates, either by platform type or by time perception mode, and that there will be no significant interaction. The alternative hypotheses are that, controlling for prior VR experience, duration estimates in VR will be significantly less accurate than those made using conventional monitor technology, and that retrospective estimates will be significantly less accurate than prospective estimates. The interaction hypothesis suggests retrospective estimates made in VR are expected to be significantly less accurate, while prospective estimates made using a conventional monitor will be significantly more accurate.

Chapter Two. Technical Overview.

2.1. Immersive Content

The VR technology employed in this study was a Meta Quest 2 HMD (Meta Platforms, Inc.), which includes proprietary tangible controllers. This is a popular platform among recreational users, with 18 million units sold as-of 2023 (TechWire Asia, 2023) and was selected for the study as being typical of the home user market. The 6DoF immersive experience for the study was selected from the Meta online store, as again representing a standard experience for the home user. VR experiences on Meta are given a ‘comfort’ rating to broadly cover potentially destabilising effects included in the experience, such as the sensation of heights, speed, flight, fear, horror, and so-on. To select an experience with heightened levels of magnitude and arousal, while still being manageable for inexperienced VR users, only experiences rated ‘Moderate’ were shortlisted for use in the study, and of these any which included horror or violence were excluded for ethical reasons.

Figure 2.1.

Example of the ‘Bay’ environment in The Climb II (Crytek GmbH, 2021) illustrating fidelity and lighting effects

Figure 2.2.

Example of the ‘Canyon’ environment in The Climb II (Crytek GmbH, 2021) illustrating hand detail and atmospheric effects

The experience selected was the VR climbing simulator *The Climb II* (Crytek GmbH, 2021) in which participants can rock climb in various digital environments, using virtual hands which are visible within the experience. *The Climb II* is a 6DoF experience, as the user is able to move within the environment, albeit only along selected routes. The user remains physically stationary during the experience, and movement within the digital environment is produced wholly by interacting with aspects of the environment such as ledges and handgrips, using the virtual hands. This was considered a positive aspect of the experience due to the associations with spatial realism discussed above, as participants' hands need to be in contact with the environment at all times, and the scale of an immersive environment can be affected by 'graspable' objects in VR, which in-turn has been shown to improve the sense of realism in high-fidelity environments (Ogawa et al., 2018).

In accordance with the reality-virtuality continuum taxonomy (Milgram and Kishino, 1994; Skarbez et al., 2021), aspects of the experience relating to world knowledge, reproduction fidelity, and presence, were generally all rated positively in user reviews online. Terms including 'thrilling', 'tension' (IGN, 2022), 'realistic', 'beautiful locations', 'fear', (6DOF, 2021), 'risk', 'vulnerability', and 'flow state' (Polygon, 2021) are common in both professional and individual reviews. Environments in *The Climb II* are highly detailed and strongly replicate real-world counterparts (although fictional, the environments are based on real-world locations such as the Alps or Iceland) with near photo-realistic fidelity. A strong sense of presence relates to aspects such as visually arresting lighting conditions within environments (Fig. 2.1.), and use of very detailed and intuitive virtual hands (Fig. 2.2.). Potentially 'destabilising' aspects of the game responsible for its 'Moderate' comfort rating, such as a sense of heights, occasional loose and unstable holds and ledges, 'jump scares' from wildlife (in the test level, a large bird unexpectedly flies out of a concealed fissure as the user reaches it), and the ability to 'fall' within the experience, also contribute to a positive analysis against the reality-virtuality taxonomy.

2.2. Participant Comfort

Reviews of *The Climb II* on the Meta online store suggested that the experience could create discomfort in some users due to the HMD pressing too firmly on cheeks and eyebrows while looking up (due to climbing) for long periods (IGN, 2022). Consequently, the Quest 2 factory head strap was replaced with a BoboVR M2 PRO+ cantilever system (bobovr.com) which incorporates a LioN battery pack behind the head for improved weight distribution, allowing the researcher to make much more precise adjustments for participant comfort during set-up. HMD-weight is known to compromise the experience for more susceptible users (Yan et al., 2019), and because the cantilever head strap slightly increased the weight of the HMD system, this was factored into the design of the study procedures (below).

Visually induced motion sickness (VIMS) is also a consideration when using VR technology (Nürnberger et al., 2021) due to the disconnect between movement perceived by the eyes and a lack of movement perceived by the inner ear, and while contemporary technologies have improved the situation considerably, it is still possible for VR users to experience symptoms such as nausea and vertigo. Wang et al. (2023) found that higher visual refresh rates (the speed at which consecutive images are created on the HMD screens) can improve susceptibility to VIMS, illustrating a 120 Hz threshold setting below which users were more susceptible to sickness. 120 Hz is the highest available setting on the Meta Quest 2 headset, and consequently this was the setting selected for use in the study.

2.3. Non-VR Participants

Examining participants using VR-specific content in a non-VR context was a novel aspect of the current research and presented some technical challenges. Firstly, because *The Climb II* is not available on non-VR platforms, the Meta Quest 2 HMD had to be used, even by non-VR participants. This meant that the HMD had to be placed on the forehead of participants (see Appendix 4). The image from the HMD could then be cast wirelessly to a computer for display on a conventional monitor. No measurable delay was recorded during this process. Participants were able to view the HMD output on the screen, and use the Quest 2 proprietary controllers to interact with the experience as normal.

A 16” 2020 MacBook Pro laptop (Apple Inc.) was selected to show the feed from the HMD in full-screen mode. Early tests experimented with using a large projected image for conventional monitor use to more closely resemble the scale of the VR experience, however varied feedback from participants suggested different experiences depending on participants’ height, and consequently a more familiar laptop screen was used for all participants whose data contributed to the study. The optimum configuration for the laptop was on a tabletop, 75cm in height, with participants undertaking the experience standing (rather than seated) to match the VR participants, who also undertook the experience in a standing position. The tabletop height was selected because in early tests with screens at participant eye-level, the raised perspective of the HMD (being positioned on the forehead, above the eyes) could be mildly disorientating. Consequently, the most comfortable approach, and the one which provided the most consistent experience for different participants, was to position the screen slightly below the eye-line, which kept the HMD level. Given the angle of view would alter based on participant height, a ratio of 17:10 was developed to determine the distance a participant would need to stand from the screen. A participant 170cm in height would consequently need to stand 100cm from the screen, while a participant 160cm in height would stand 94cm from the screen and so-on. While this was only a basic ratio developed as an aggregate of early participant experiences, it nevertheless ensured consistency across all participants, which was the primary goal.

Finally, due to the challenge of viewing a 360-degree experience on a fixed-position laptop screen, conventional monitor participants needed to be shown how to recalibrate their view using the ‘home’ button on the right-hand controller, to allow them to more comfortably view oblique angles if required. This was factored into the design for the study procedures (below).

2.4. Study Design Considerations

Early designs for the current study aimed to include a measure of participant achievement within the game, to ascertain whether time compression might be related to task difficulty. Ultimately this was not recorded due to variations in the ways that participants approached the experience. In early tests some participants wanted to see how far they could climb within the allotted time, while others wanted to explore new and varied routes around the mountain rather than aiming to reach the finish, and some actually stopped climbing for periods just to enjoy the scenery. Some participants even began to fall deliberately, reporting that they enjoyed the sensation of falling in VR. Consequently, task difficulty could not be accurately judged against a single metric as in other previous studies such as Mullen and Davidenko (2021) where completing mazes was the only objective. Additionally, because that study found no relationship between time perception and task difficulty, the process was not included in this study.

Due to the expectedly higher levels of arousal and valence compared to previous studies which have not used VR-specific 6DoF experiences, a longer duration of ten minutes was planned as the set time interval. This was based on the potential of VR experiences to produce initially high levels of physiological response (autonomic activity; Estupiñán et al., 2014), to allow participants longer to acclimatise to the study level, and produce more consistent results (Rutrecht et al., 2021). However, in early tests it became apparent that ten minutes may be too long for some inexperienced VR users, as the climbing experience can produce particularly strong autonomic responses (some participants reported feeling 'shaky', 'sweaty' and 'holding themselves stiffly' perhaps due to concerns about heights and falling) and the set duration was subsequently shortened to eight minutes and thirty seconds. The eight-minute duration was commensurate with prior studies such as Mallam et al. (2020) while the decision to move to a half-minute was due to the potential for rounding bias in the retrospective condition (Huttenlocher et al., 1990).

Chapter Three. Method.

3.1. Participants

Power analysis using G*Power (Erdfelder, 1996), based on planned ANOVA analyses, indicated that to achieve a medium effect size of .35 using Cohen's *f,* with probability of .05, a minimum sample size of 68 participants was required to achieve .80 power (see Appendix 5). There were no exclusion criteria applied to participants except age (participants needed to be aged 18 and above), while any known susceptibility to VR-related problems such as visually induced motion sickness (VIMS; Nürnberger et al., 2021) was asked to be declared, whereupon participants could be allocated to the non-VR factor. In practice, this was not applied as no participants declared any prior difficulties with VR, and consequently all participants were randomly allocated to their study group.

Participants constituted an opportunity sample, and were primarily recruited using posters positioned around three University of Gloucestershire campuses, and participant word-of-mouth. A sample of 68 individuals (39 Female, 27 Male, 2 Non-Binary, mean age = 29.5 SD = 12.5) including University of Gloucestershire students and members of the public participated. Some University of Gloucestershire students participated for course credit.

3.2. Design

A 2 x 2 independent measures factorial design was utilised. The first factor was time perception mode (Retrospective Time Perception [n= 32] versus Prospective Time Perception [n= 33]) and the second factor was immersive platform type (VR [n= 35] versus Conventional Monitor [n= 30]).

The dependent variable for the study was the accuracy of participants' estimations in comparison with the target duration of 510 seconds (8.5 minutes). The rationale for this decision was that an analysis of duration estimate alone would not provide a clear picture of any variance between the time perception modes. As discussed above, the comparison between actual time elapsed and the participant estimation was needed to determine whether estimates in retrospective and prospective factors were over or underestimations.

3.3. Materials

All participants played *The Climb II* (Crytek GmbH, 2021). Participants in VR conditions used a Meta Quest 2 HMD (Meta Platforms Inc.) and the proprietary device controllers, while participants in the conventional monitor conditions viewed the image from the HMD on a 16" Apple MacBook Pro (Apple Inc.) and used the same controllers. The rationale for selection and use of these devices and platforms is outlined in the Technical Overview chapter above.

In *The Climb II*, there are various customisable elements, such as the gender of the climber (Female or Male), the skin colour of the climber's virtual hands, and a range of wearable accessories including gloves, bracelets, and watches. All participants were assigned the same full-fingered gloves to ensure visible skin-colour was minimal. This was to limit the effects of any confounding variables from participants potentially experiencing varied levels of immersion due to more or less accurate skin colour for their virtual hands, as accuracy of an embodied avatar can affect levels of immersion (Unruh et al., 2021). No virtual watches or other accessories were included on participants' virtual hands.

Upon completion of the task, participants were asked to complete a questionnaire developed specifically for the present study. The questionnaire was completed online using the Jisc Online Surveys platform (Jisc.ac.uk). Questionnaires were different depending on whether participants were in a retrospective or prospective factor. Participants in the retrospective factor completed a questionnaire with eight questions intended to provide context to the research for the purposes of discussion, and also to potentially provide covariates in additional analyses. Participants in the prospective factor completed the same questions, except that question 7 was removed. The questions were:

1. How much prior experience do you have with virtual reality?
2. Have you had any previous rock-climbing experience?
3. How immersed were you in the virtual climbing experience?
4. How aware of your body were you during the experience?
5. Did you find yourself thinking of other things (unrelated to your experience) while you were in VR?
6. Did you enjoy the experience?
7. As precisely as you can, in minutes and seconds, how long do you feel your VR experience lasted? Please avoid rounding up/down, as your experience was specifically timed.
8. How confident are you in the accuracy of your time perception?

Participants responded on a five-point Likert scale, with 1 being the lowest value, and 5 being the highest for each question. A higher score indicated high levels of prior experience, immersion, and enjoyment. Participants' prior experience of both VR and climbing were assessed, because they could have potentially contributed to a number of factors including familiarity, confidence, and immersion. Questions on levels of immersion and embodiment were similar to previous studies such as Mullen and Davidenko (2021), representing aspects of theoretical debates relating to VR and time perception. 'Thinking of other things' was related to an approximation of attentional control and stimulus being attached to the experience, while 'enjoyment' related to the potential for emotional states such as fear and excitement, which have been shown to affect time perception (Campbell and

Bryant, 2007). Finally, 'confidence levels' could give an indication of the extent to which a participant may be aware of any time distortion that they might have experienced.

To determine the accuracy of each participant's time estimation (the DV), a calculation was performed to determine the deviation of each participant's estimate from the target duration. This calculation varied depending on whether an estimate was an under- or over-estimate of the target duration. For all timed overestimations, irrespective of factor, the target duration of 510 seconds was subtracted, so that the data only reflected the number of seconds by which each estimate exceeded the target duration. Conversely, for all timed underestimations, each estimate was subtracted from the 510-second target duration, so that the data reflected the number of seconds by which the estimate was under the target duration.

As discussed, there are oppositional underlying processes behind retrospective and prospective judgements which result in separate paradigms of study, and separate analyses of data. While retrospective estimates reflect the cognitive process of the participant (i.e. an overestimation of the target interval equates to an overestimation of the time spent on-task), prospective estimates are inverted. A prospective overestimation of the target interval illustrates an *underestimation* of the time spent on-task; in this case a participant overestimating the target interval believes they have been in VR for less time than they actually have. This could result in a statistical aberration, whereby divergent data between retrospective and prospective factors could appear to be significant. For example, a mean retrospective timed overestimation and a mean prospective timed underestimation could appear to be significantly dissimilar to the extent of potentially returning a large statistical effect size, and yet this would not illustrate the picture revealed by the data. Instead, a calculation is required to ensure the data illustrates that (in this case) mean average overestimations have been recorded in both factors.

3.4. Procedure

Participants signed up at a convenient time and were provided with a Participant Information Form via email prior to the test, and provided informed consent by completing a Consent Form upon their arrival at the test space, being made fully aware of their right to withdraw both during and after the experiment. The experiment was undertaken at several locations on University of Gloucestershire campuses. Participants were provided with standardised instructions based on the factor and level they had been randomly assigned to. Participants completed the experiment individually, only the participant and researcher were present.

All studies were undertaken in a room with closed doors and windows to limit extraneous sounds. All participants were asked to set phones, smart watches, and other notification devices to silent, and to leave them with the researcher during the study, to ensure any notifications, such as vibration alerts, did not affect either immersion levels, or potentially provide a sense of duration. No clocks could be seen or heard in the test spaces.

HMD-weight can compromise the experience for more susceptible users (Yan et al., 2019), and because the cantilever head strap slightly increased the weight of the HMD system (see Technical Overview chapter above), all participants were asked to hold the HMD to get comfortable with the weight prior to the study, and verbally consent to continue before placing it on the head. While all participants wore the same virtual gloves within the experience (see above) an appropriate skin colour was also selected for each participant relating to the small amount of skin visible on the virtual wrist not covered by the gloves. Watches were removed from all participants' virtual hands, and each participant was asked to verbally state whether they would prefer to play as a male or female climber during set-up, to ensure trans and non-binary participants did not have this decision made for them based on the researcher's assumption. Participants in VR conditions wearing glasses were able to do so using an optional glasses 'spacer' within the HMD.

VR can sometimes produce feelings of discomfort, including dizziness and nausea, and due to the added potential for fear of heights and falling in this specific experience, all participants were shown how to immediately pause and exit the experience should they need to. One participant did so, reporting an immediate feeling of discomfort from the perceived heights in the climbing experience; the participant was monitored and left the test space once they felt comfortable to do so, reporting no ill effects afterward. Their data was not included in the study results.

Figure 3.1.

Example of practice level 'Slide or Shortcut' in the 'Freestyle' environment, featuring male hands, the full-finger gloves used in the study, and the darkest available skin colour

Figure 3.2.

Example of test level 'The Boar's Tusk' in the 'Alps' environment, featuring female hands, the full-finger gloves used in the study, and the lightest available skin colour

Upon completion of the climbing task, all participants were asked to sit and to report any ill effects to the researcher. A small number of participants reported mild feelings of dizziness, and they were asked to remain in the test space until they felt able to leave. None of these participants wished to see a University of Gloucestershire first aider when asked, and no participants left the test space still reporting any ongoing ill effects.

Before undertaking the climbing task, participants were invited to undertake a non-timed practice period to get used to the feel and mechanics of the experience, so that familiarity would not constitute an extraneous variable. This was undertaken in the '*Slide or Shortcut*' level within the '*Freestyle*' environment (Fig. 3.1.). While most of the environments in *The Climb II* are near-photorealistic representations of real-world environments, the *Freestyle* environment is a fantasy level involving climbing on colourful geometric shapes floating in a cloudy sky. The rationale was to improve comfort levels during practice, as the experience is clearly a non-real fantasy, allowing participants to experience the mechanics and potentially destabilising effects of the experience (such as falling) without it feeling too 'real' from the outset. Once each participant had verbally indicated that they were happy to end their practice period, the participant themselves launched the test level. This was the first and easiest level in *The Climb II* - the *'Boar's Tusk'* level in the *'Alps'* environment (Fig. 3.2.), and participants were asked to play in 'Casual' mode, which removes some complicated game features to keep the experience as simple as possible.

When asked to judge the duration of the interval retrospectively, participants were all instructed with the same language: '*please try to make your estimate as precisely as you can, in minutes and seconds, as the interval was specifically timed*', with the aim that such language might prime participants to avoid rounding to the nearest minute (Kahneman, 2013).

Participants in the prospective factor were informed before the practice session that they would be asked to undertake a duration estimate, and after the participant had launched the test level, they were informed of the 8.5-minute target duration while the level was loading. Each participant was then asked to repeat the target interval back verbally before beginning to climb, as early studies indicated some participants might forget instructions leading to unusable results. Participants in prospective conditions were also asked to verbally cue the stopwatch timing the experience to ensure they had a clear starting point ($t = 0$) in mind. Participants in the retrospective conditions were not given any cues relating to time beforehand, and all were simply instructed to 'climb until asked to stop'.

Participants were asked to complete the questionnaire relating to their time perception mode upon completion of the climbing task. After completion of the questionnaire, participants were debriefed and provided with a Debrief Form and a copy of their Consent Form via email.

Chapter Four. Results.

Whilst participants' level of experienced immersion and declared previous experience in VR was intended to be used as a covariate within an ANCOVA, assessment of the assumption of homogeneity of regression slopes indicated that means could not be adjusted equally across levels of the factors. Due to this violation, an ANOVA was, instead, utilised.

The parametric assumptions were that the data were independent, there was homogeneity of variance, data was normally distributed, and there were no outliers. The design was independent because participants only took part in one level of each factor. Levene's value for data including outliers was $p = .468$, supporting the assumption of homogeneity of variance.

To assess distribution, screening was conducted at each level of each factor, by dividing the skewness statistic by its standard error and the kurtosis statistic by its standard error. Normal distribution was assumed when values of skewness were in range of +/- 2.58, and kurtosis values were in range of +/-2. Whilst initially all bar two of the levels violated normality (see Table 1), when the 3 outliers (all in the VR factor; two in the retrospective level and one in the prospective level – see Appendix 6) were removed the data was normality distributed (see Table 2).

As all outliers occurred within the VR condition, they may have been a result of specific responses to the technology, such as the newness and/or novelty value of VR, or susceptibility to immersion in the VR technology. This might include forgetting instructions (such as forgetting to monitor the 8.5-minute time interval in the prospective level due to novelty distractions) or varying motivational factors (as discussed above, some participants tried to get as far as they could within the timeframe while others liked to stop to view their surroundings, and some even chose to fall repeatedly). As analysis suggested that removal of the outliers provided a clearer picture of central tendency and variability due to more normalised distributions, results are reported with the outliers removed from the dataset (however, including them did not change the interpretation). Removal of the three outlier scores means that data is reported from a sample of 65 participants (37 Female, 26 Male, 2 Non-Binary, mean age= 29.4 SD= 12.3).

Table 1.
Assessment of distribution: Skewness and Kurtosis values for each level of platform type and time perception mode.

	Skewness				Kurtosis			
	Statistic	Std. Error	Value	Assumption Satisfied	Statistic	Std. Error	Value	Assumption Satisfied
Virtual Reality	1.511	0.383	3.945	No	2.922	0.750	3.896	No
Conventional Monitor	0.735	0.427	1.721	Yes	0.230	0.833	0.276	Yes
Retrospective Perception	1.503	0.403	3.729	No	3.065	0.788	3.889	No
Prospective Perception	1.368	0.403	3.394	No	3.731	0.788	4.734	No

Table 2.
Screening process for data with outliers removed

	Skewness				Kurtosis			
	Statistic	Std. Error	Value	Assumption Satisfied	Statistic	Std. Error	Value	Assumption Satisfied
Virtual Reality	0.682	0.398	1.713	Yes	0.364	0.778	0.467	Yes
Conventional Monitor	0.735	0.427	1.721	Yes	0.230	0.833	0.276	Yes
Retrospective Perception	0.670	0.414	1.618	Yes	-0.233	0.809	0.288	Yes
Prospective Perception	0.068	0.409	0.166	Yes	-1.465	0.798	1.835	Yes

To test whether Platform Type and Time Perception Mode influenced estimation accuracy, a 2 (Platform Type: VR versus Conventional Monitor) x 2 (Time Perception Mode: Prospective versus Retrospective) independent measures factorial ANOVA was conducted on the accuracy of participant estimations compared to the target duration of 510 seconds. There was a significant main effect of ‘time perception mode’, $F(1, 63) = 5.71$, $p = .020$ ($\eta p^2 = .086$, observed power = .65) such that participants undertaking estimations prospectively were significantly more accurate (*M* = 130.1 seconds, *SD* = 81.5 seconds, 95% CI = [101.2, 159]) than participants undertaking estimations retrospectively (*M* = 188.8 seconds, *SD* = 114.3 seconds, 95% CI = [147.6, 230]) by a margin of 58.7 seconds. There was a non-significant main effect of ‘platform type’, $F(1, 63) = 1.49$, $p = .227$ ($\eta p^2 = .024$, observed power = .23) such that there was no significant difference between estimations made using VR (*M* = 172.5 seconds, SD = 107.5 seconds, 95% CI = [135.6, 209.5]) and estimations made using the conventional monitor (*M* = 143.2 seconds, SD = 95.9 seconds, 95% CI = [107.4, 179]). Additionally, there was a non-significant interaction between time perception mode and platform type, $F(1, 63) < .001$, $p = .990$ ($\eta p^2 = < .001$, observed power = .05) indicating that participants undertaking estimations in both time perception modes were not affected by the platform they were using.

Several previous VR chronoception studies, such as Mallam et al. (2020) and Walker et al. (2021) have included average estimation inaccuracies in the form of percentages. To aid discussion of comparison with these studies (below), in the current study average prospective estimates deviated by 25.5% from the target duration of 510 seconds, while retrospective estimates deviated by 37% of target duration. Average estimates made in VR deviated by 33.8% of the target duration, while estimates made using the conventional monitor deviated by 28.1% of the target duration. An average inaccuracy of 158.3 seconds (2.6 minutes) was found across the study, equating to 31% of the target duration of 510 seconds.

Additionally, the study found a high level of variance in estimate accuracy, with average estimates being drawn from a broad range of results. VR estimates ranged from a 7-second deviation from the 510-second target to a 425-second deviation, conventional monitor estimates ranged from a 1-second to a 390-second deviation, retrospective estimates ranged from a 1-second to a 425-second deviation, and prospective estimates ranged from a 7-second to a 390-second deviation.

Chapter Five. Discussion.

5.1. Overview

The aim of the present research was to investigate reported distortions in the perception of time (chronoception) in virtual reality experiences, and additionally the phenomenon of 'time compression' (Mullen & Davidenko, 2021) which has been associated with the technology. The current research investigated the potential effects of time perception mode and platform type on time duration accuracy in VR.

As hypothesised, duration estimates made retrospectively were less accurate than those made prospectively, and participants in both time perception modes overestimated the target duration on average. Observed power of .65 suggests that the medium effect size indicated (.086) can be inferred with some confidence, although this is the first known study to test VR time perception against both perception modes, and as with any study which is the first of its kind, further research will be required to verify this finding.

The finding supports the existing literature, as significant differences in estimate accuracy between time perception modes have been found in previous studies (Block & Zakay, 1997; Walker et al., 2021) with retrospective estimates typically less accurate than prospective estimates. While the non-significant main effect of platform type, and the non-significant factor interaction mean that participants undertaking estimates in both time perception modes were not affected by the platform type they were using, all participants made estimations while engaging with the same 6DoF content. As such, the current finding suggests that established differences in estimate accuracy between time perception modes may remain consistent when engaging in immersive 6DoF content.

Contrary to the hypothesis, there was no significant difference in estimate accuracy by platform type. Observed power of .23 and a small effect size (.024) indicate that there is no meaningful difference to find between estimates made in VR and those made using a conventional monitor. It is possible that this may be the result of a limitation of the study design, as the current study is commensurate with previous VR chronoception studies outlined above (Schatzschneider et al., 2016; Rutrecht et al., 2021; Unruh et al., 2021) which have found significant time distortion effects, but have not found a difference between VR and a comparison (non-VR) technology. As discussed, earlier studies have focused on the VR HMD technology specifically, and in finding time distortion effects with no significant difference between HMD and non-HMD conditions, it is likely that some other shared aspect of the VR experience which has been consistent throughout each study (such as the immersive content and/or control mechanisms) is more directly responsible for the time distortion effects found. This effect appears to have been replicated in the present study, as a significant time distortion effect was found in the 'time perception mode' factor, while the effect was not found in 'platform type' suggesting that, similarly to earlier studies, some aspect of the study task shared across both platform types was the probable cause.

In the present research, the shared aspect of the experience most likely to be responsible for this outcome is the VR-specific, 6DoF experience which was undertaken by all participants in both VR and conventional monitor conditions. This conclusion is based on considerations outlined in the Introduction. In previous chronoception research examining VR against a comparison technology, the aspect of each study consistently shared by participants in VR and non-VR conditions has been the content employed. By contrast, studies have varied in their use of control mechanisms. Van der Ham (2019) examined participants estimating film clips in VR and in a cinema without any handheld controllers, Mullen (2023) used a conventional games console controller in VR and non-VR conditions, and Mallam et al. (2020) used VR-specific controllers. As each study (and others) found time distortion effects without significant differences between VR and a comparison technology, based on consistently-shared content and inconsistently-employed control mechanisms, a possible inference is that the immersive content is the main variable of interest to VR time perception studies.

An additional aspect of prior research points toward this conclusion. Nuyens et al. (2020) found that regular (non-VR) gamers exhibited similar retrospective perception to non-gamers in neutral contexts, and impaired perception compared to non-gamers when aroused by gaming stimuli. Should such a finding be replicated in VR, this could provide clarity to the theory that the HMD is not primarily responsible for chronoception-distortion effects. Of the three components of a VR experience (HMD, content, and controllers), if stimuli responsible for chronoception-distortion effects are specifically related to the HMD, a more pronounced effect would be anticipated in studies employing a comparison to non-HMD technology, because non-HMD participants would be likely to experience reduced or no VR stimulus. An indicator of this would be the estimations of participants with high levels of prior VR experience. Should the estimates of experienced VR users made using an HMD be notably less accurate than those made using a non-HMD technology, this would suggest a more pronounced level of VR stimulus from the HMD. Conversely, should participants with higher levels of VR experience return similar levels of estimation inaccuracy in HMD and non-HMD conditions, this may point toward the 6DoF experience or tangible controllers, and/or a combination of the VR variables, rather than the HMD specifically, as contributing to any time distortion effects found.

In the present research, analyses using levels of prior VR experience as a covariate showed a violation of regression slopes, so ANCOVA analyses were disregarded. Consequently, no conclusions can be drawn in this respect. This suggests either that there was no effect to find, or that this is a limitation of the current study. Based on the findings of Nuyens et al. the latter supposition is likely, and further research is required to determine firstly whether the findings are replicated in VR, and secondly to clarify the role of the HMD in VR time perception. Of the 65 participants in the current study, 51 declared their prior VR experience to be 'little' or 'none', and only 6 participants rated their prior experience as being 'high' or 'very high'. Consequently, no conclusions relating to the findings of Nuyens et al. can be developed in the current study. The low level of prior VR experience within the study also relates to other aspects of the findings, and will consequently be developed further below.

Contrary to the hypotheses, the interaction between the factors was non-significant, with no effect found. Use of platform type had no effect on the accuracy of participant estimates in either time perception mode. While the study satisfied homogeneity of variance analyses, participant estimates fell within a broad range (see Results section above). VR estimates ranged from a 7-second to a 425-second deviation from the 510-second target, for example. Again, this may have been the result of a limitation in study design. In addition to suggesting a high level of within-group variance which may be reflected in the non-significant finding, the range of participant estimates may point to varied experiences of participants, which the study design was not equipped to find. One observed outcome was that some participants wanted to climb as far as possible within the timeframe, while other participants preferred to pause to look at the scenery, and a small number of participants enjoyed the sensation of 'falling' and did so repeatedly. The study included no metric of success by which participant experience could be ascertained; if participants had been instructed to reach a checkpoint in the shortest possible time, this could have provided a more standardised experience for all participants. An additional benefit of such a success metric could be that participants may not have needed to be provided with a target duration. Mallam et al. (2020) studied participants undertaking a searching task in VR and non-VR conditions, and participants were asked to judge the time they had taken to find various items. Linking the perception of duration to some form of participant success, rather than a more abstract unit of time, might have reduced the within-group variance found in the current study, and represents a potential avenue for further VR chronoception research.

5.2. Time Compression

As participants in the present research overestimated the target duration on average in all factors and levels, the findings are inconsistent with time compression (Mullen & Davidenko, 2021). The findings are also not supported by influential time perception literature as Block and Zakay's (1997) meta-analysis of time perception studies found that both prospective and retrospective estimations of duration are typically underestimations. As noted above, most time perception studies, such as those primarily analysed by Block and Zakay, have employed interval durations of less than 2 minutes, and estimations have been shown to alter with longer durations. Walker et al. (2021) found overestimations of an 8-minute cognitive load task by more than 33% on average in both time perception modes. This is commensurate with the present research which found overestimations in both time perception modes of an 8.5-minute task by an average 31% of the target duration. Walker et al.'s study found longer (and consequently less accurate) estimates in the prospective estimation mode, which supports Block and Zakay's findings of longer prospective estimates (although in that case, longer underestimations meant that prospective estimates were more accurate), but is not supported by the present research, which found that prospective estimates were both shorter and more accurate than retrospective estimates. The present research does support the findings of the only other known study of VR time perception to use a matched-content study design with a commercially available (although not VR-specific) 6DoF experience (Mallam et al., 2020) which found retrospective overestimations in both VR and conventional monitor conditions by an average of 20.3% of target duration.

Given that the results of the present research and other studies appear inconsistent with time compression, further analysis is required to determine what conclusions can be drawn to develop understanding of the phenomenon. As discussed above, being subserved by different cognitive processes, prospective and retrospective judgements are susceptible to influence by varied factors including cognitive load, allocation of attentional resources, novelty and magnitude of stimulus, emotional responses, and the amount and variation of memories accumulated during an interval. Based on the average overestimations recorded in the present research, comparison between the study findings and those variables from the existing literature which have been shown to contribute to overestimations in time perception is necessary.

Several factors have been discussed above which have been shown to increase duration estimates across both prospective and retrospective perception modes. The magnitude (Xuan et al., 2007; Matthews et al., 2011) and novelty (Matthews & Gheorghiu, 2016) of a stimulus have been shown to affect time perception, with high levels of magnitude and novelty both associated with increases in perceived duration prospectively and retrospectively. Most participants in the present study declared little or no prior experience of VR, meaning that use of the technology may have been a novel experience for many. No participants declared prior experience with *The Climb II* or climbing simulators more broadly, so that the immersive content presented a novel experience for all participants. Consequently, the novelty of stimuli involved in the study is likely to have contributed to time distortion and as novelty is associated with increased duration perception in both time perception modes, this conclusion is supported by the overestimations found. Overestimations of duration are not commensurate with time compression, however, suggesting that time compression may associated with familiarity rather than novelty, and experienced VR users may be more susceptible than novices. This inference is supported by other aspects of the current study, which will be developed further below.

Emotional responses to stimuli also affect both time perception modes, although findings have been mixed. VR experiences have been associated with high levels of arousal (Estupiñán et al., 2014; Lemmens et al. 2022) which can also be evoked by novelty, and which is known to produce longer estimations of duration (Gil & Droit-Volet, 2012). Experiences associated with fear and trepidation have also been shown to increase subjective time (Campbell & Bryant, 2007). The unfamiliar VR technology in the present study may have caused feelings of trepidation in some users (Hurler, 2021), while the content employed (*The Climb II*) is designed to produce a somewhat destabilising emotional response, as participants are placed in precarious situations involving perceived heights. The photorealistic environments of the experience combined with a sense of danger due to 'falling' suggest a high level of magnitude for many users, a conclusion supported by online reviews of the experience discussed in the Technical Overview chapter above. Given that the content experience was unfamiliar for all participants, these aspects of the study also seem likely to have contributed to the overestimations of interval duration found. Similarly to the effect of novelty on time perception (above), high levels of stimulus magnitude and associated overestimations are not commensurate with time compression, suggesting that the phenomenon may be associated with lower levels of magnitude. While further studies will be required to examine this, it is possible that for both magnitude and novelty, there may be a connection with interval length.

The average VR session is typically around 30-45 minutes (NRG, 2022) and it may be that the level of magnitude and novel aspects of a VR experience are more typically associated with shorter durations, such as the 8.5 minutes used in the current study. As the only other known study to test VR time perception with a commercially available 6DoF experience, and tangible VR controllers, Mallam et al. (2020) may support this conclusion. Mallam et al. found retrospective overestimations in both VR and conventional monitor conditions utilising an interval of 8 minutes. The present research and Mallam et al.'s study produced some similarities in results, and both studies seem to accord with Vierordt's Law since they could be argued to have used short duration estimates. The operational definition of 'short estimates' is unclear in Vierordt's Law, although the transition between 'short' and 'long' durations has been suggested to be between 2 and 10 minutes, depending on task (Roy & Christenfeld, 2008; Yarmey, 2000). Further study is required to compare VR time perception against varied study durations, specifically to determine whether longer durations may produce time compression effects. The average VR session of around 30-45 minutes constitutes a clear 'long duration' according to Vierordt's Law, which may be more likely to produce underestimations of duration. Taken together, the employment of a stimulus with a high level of magnitude and arousal, with primarily novice VR users more susceptible to the novelty of the experience, and utilising a short task interval, suggests the current study may have been predisposed toward overestimations of duration. As such, it was consequently unlikely to produce findings to further understanding of VR time compression. Despite this, there was a significant difference found between time perception modes which still requires further discussion.

Retrospective perception was the time perception mode with the most pronounced time perception inaccuracy in the current study, and consequent time distortion experienced by participants. While overestimations in the current study may be attributable to variables such as magnitude and novelty, which are known to affect both time perception modes, the significant difference found between prospective and retrospective estimations suggests that factors specifically related to individual modes may also have contributed to the findings. Retrospective perception models, such as the Contextual Change Model (Block & Reed, 1978), are memory-based, and retrospective duration estimates increase with greater amount of stored and retrieved information (Ornstein, 1969), number of recorded changes (Fraisse, 1963) or amount of demarcation and variation between events during an interval (Poynter, 1983). Recorded overestimations in the retrospective level consequently suggests that the 6DoF test experience has produced an increase in at least one of these values. There are few instances of change or variation in the test level of *The Climb II*, as participants work their way through an environment which is consistently similar throughout. Specific instances such as participants 'falling' may provide unique stimuli for individuals (i.e. a participant who falls three times may use these experiences as markers for retrospective time perception), although not all participants experienced falling. Some reported that they were pleased they had not fallen as they did not want to experience the sensation, and it was therefore not a consistent experience for all. Consequently, it is likely that, of the three variables, there has been an increase in the amount of stored and retrieved information which participants have drawn upon when making their estimates, rather than the number of changes or events.

As overestimations are oppositional to time compression, it is possible that the phenomenon is associated with a decrease in the amount of stored and retrieved information available to determine duration. Studies of memory formation in VR have produced mixed results, and such a conclusion is not possible without further research. It may also be that there are additional factors associated with VR which may need to be considered. As discussed above, while not tested by any known research to-date, anecdotal evidence of VR temporal 'warping' (Appendices 10, 11, 12) suggests that time compression may be experienced differently in VR compared to real-world situations. Time may appear accelerated in VR which could be viewed as a form of virtual 'temporal mechanics' (Jarvis, 2021), a phenomenon which titles such as such as *American Truck Simulator* (SCS Software) are responding to with 'warp' adjustment features which allow temporal game mechanics to be naturalised to individual preferences. Instead of time becoming ‘lost’, perception of VR time compression may be that accelerated time is ‘compressed’ into a shorter duration. Such a conclusion may be supported by the findings of Bogon et al. (2023) who found that judgement of abstract time units in VR did not produce any distortion effects compared to the non-VR condition, while judgement of a physical process led to an increase in perceived interval duration in VR compared to a real-world experience. This may be due to unique aspects of the technology, as there are various factors which could account for such VR-specific temporal ‘warp’ experiences. It may be, for example, that due to the sensory isolation from the outside world created by the HMD (and additional factors such as immersive audio technologies) VR time perception is prone to being affected by additional variables compared to time perception in normal circumstances. As discussed above, factors including screen refresh rates (Wang et al., 2023), virtual zeitgebers (Schatzschneider, 2016), spatial realism (Kaplan-Rakowski & Gruber, 2019; Lemmens et al., 2022), interactive control mechanisms (Palombo et al., 2024) and cognitive absorption (Agarwat & Karahanna, 2000; Zhang et al., 2006) have all been shown to affect perception within VR experiences in various ways, and time perception may be part of this. The anecdotal nature of the evidence currently supporting such inferences means further research will be required before any conclusions can be drawn in this respect, although if verified, such factors may affect retrospective time perception specifically. Prospective time perception is associated with an attentional balance between stimuli and temporal processing, as time is a known factor. Retrospective perception, in contrast, is developed from available information after an interval has elapsed, and consequently such VR specific variables may alter the process of retrospective perception in VR compared to real life. VR temporal ‘warping’ might mean that a retrospective estimate could potentially be based on a large number of stored and retrieved memories, and yet if each memory is based on a perception of accelerated temporal mechanics, an underestimation of duration may still be possible. Given the overestimations found in the present research, it may also be that VR temporal ‘warping’, if verified, may be associated with longer interval durations than the ‘short’ duration used in the current study.

Again, the findings of Mallam et al. (2020) may support this conclusion. Test participants undertook a task searching for items within a 6DoF digital environment, estimating the duration of the task upon completion. Participants completed three search tasks, and while search accuracy increased with experience, indicating learning behaviours and accurate memory formation across the study, time perception estimations did not improve, and remained consistently overestimated regardless of search-task success. In conjunction with the current study, the finding suggests that retrospective estimates in VR may not be wholly associated with memory and may consequently deviate from established retrospective models and paradigms. Further research will be required to verify such a conclusion, and may need to examine the nature of VR time compression itself more closely, given the anecdotal discussion of VR time compression (Appendices 10, 11, 12) as varying from other contexts.

While retrospective overestimations seem to accord with existing literature concerning VR and time perception, the prospective overestimations recorded by the present research are less clearly supported. The same novel and high-magnitude stimuli which may have caused a greater amount of stored and retrieved memories from which to judge the interval duration retrospectively ought to have returned oppositional effects in prospective judgement. In prospective estimations attention is allocated between stimulus and temporal processing, so that increased attention to stimulus diverts attention away from temporal processing, leading to shorter duration estimates. Increased cognitive load is also associated with shorter duration estimates as attention is allocated away from temporal processing (Thomas & Weaver, 1975). Conversely, prospective estimations are thought to increase with greater allocation of attention to temporal processing, simpler and/or smaller numbers of stimuli, stimuli which do not require the participant to react/interact, and without the need to divide attention between different stimuli (Block & Zakay, 1997). Accordingly, one or more of these variables is likely to have contributed to the overestimations found in the present study, although the lack of a significant difference between HMD and conventional monitor prevents any conclusions in this respect, so that further discussion is speculative. The nature of VR as an enclosed visual system means that participants' attention is not normally divided between varied visual stimuli outside of the VR experience, which may have produced overestimations. Similarly, simple and/or small numbers of stimuli may have also contributed to the result, given that the test level in *The Climb II* is consistently similar throughout. Importantly, a key aspect of the 6DoF experience is that all participants were required to interact with, and react to, the digital environment, and this should have produced shorter estimates, according to the established literature. Consequently, the findings of the current study appear to contradict both the phenomenon of time compression, and previous studies of prospective perception more broadly. At the same time, prospective perception in the current study was significantly more accurate than retrospective perception, and the overestimations found may be more associated with universal factors relating to overestimations in both modes, such as the magnitude and novelty of the stimulus, rather than prospective perception more specifically.

What prospective VR time perception may do is highlight a potential inconsistency with the prospective paradigm, as the allocation of attention toward stimuli and away from temporal processing is thought to produce shorter estimations, and yet this may, to some extent, contradict aspects of the paradigm. The conceptual Attentional Gate Model (Block & Zakay, 1996, 1997) posits that an internal pacemaker produces pulses similar to the 'ticks' of a clock; pulses are said to pass through an 'attentional gate' which becomes wider as attention is allocated to temporal processing, and narrower as attention is allocated elsewhere. Importantly, the rate of pulses used to assess duration is a function of arousal; higher levels of arousal produce more pulses. The potential contradiction is that, based on the principle of cognitive absorption in digital technology (Agarwat & Karahanna, 2000; Palombo et al., 2024; Zhang et al., 2006;), if the stimulus is the source of arousal, the magnitude of the stimulus increasing arousal (and consequently pulse-rate) will also increasingly allocate attention away from temporal processing simultaneously, thus narrowing the attentional gate. This should mean that fewer pulses can be recorded, irrespective of pulse-rate, and overestimations of prospective time perception should therefore be unlikely to occur when using digital technologies. The prospective overestimations recorded in the present research, and in existing literature such as Walker et al. (2021) suggest a stage of arousal whereby the attentional gate can remain open (i.e. attention can still be allocated to temporal processing) independently of stimulus, so that a sufficiently high level of arousal can produce a pulse-rate capable of overestimation in the conceptual model. In a VR experience, attention is allocated to a single stimulus with potentially high levels of magnitude, novelty, and emotional response. High levels of arousal would be anticipated which should generate a high pulse rate, while the single stimulus may also allow for allocation of attention to temporal processing. Consequently, prospective overestimations in VR may be likely. This contradicts the principle of 'time compression' however, and further research will be necessary to investigate prospective overestimation of duration in VR. Should further research illustrate that VR time compression is only connected to retrospective processing, for example, this interpretation of the prospective paradigm would be supportable without contradiction.

The findings of Bogon et al. (2023), that perception of event-duration in VR varied compared to real-world experiences, with no corresponding variance in the conception of abstract units of time, may support this theory. Bogon et al. employed a matched-content

(VR/non-VR) study of interval production tasks using prospective perception, and concluded that VR may not change the sense of time but may instead change expectations about the duration of physical processes. While this study employed short interval estimations of up to 8 seconds, which may not support direct comparisons with longer-duration studies, the conclusions may still be supported by the present research. As this was a prospective judgement test, the finding suggests that participants actually underestimated the duration in VR compared to the non-VR condition. Nevertheless, the results offer an intriguing conclusion which requires verification by further research. Comparison to the present study offers a potential explanation of divergence between prospective and retrospective factors. Prospective and retrospective estimates are subserved by different cognitive processes, and it is possible that the findings of Bogon et al. (2023) are only applicable to the prospective processes tested in the study. Based on the conceptual models for each time perception mode, changes in expectations of duration would only be applicable to prospective judgements, where time is a known factor, rather than the memory accumulation of retrospective judgements. Further research is needed to investigate this hypothesis, but the conclusion that VR affects time perception *only retrospectively*, and changes expected duration judgements prospectively, would be an important finding.

Finally, it may be that some variation of the so-called 'Hawthorne Effect' (McCambridge et al., 2014) whereby the results from participants who are aware of being studied vary from those who are not, may have contributed to the results. Participants in the prospective level alone knew that temporal processing constituted part of the study, and may have allocated more attentional resources to this accordingly. Therein lies a limitation of the present research study design. There was no metric of success within the study comparable to other studies such as Mullen and Davidenko (2021), for example, where participant success could be measured by how many levels of a maze game were completed within the time interval. As discussed, measurement of some similar metric, such as how far through the climbing level participants could progress in the time interval, could have been instructive if it showed a variation between prospective and retrospective factors. Such a result could have been a potential indicator of the allocation of attentional resources to temporal processing balanced with the need to complete the task with the best possible result. As it stands, the possibility that some variation between time perception modes relates to the knowledge of the variables being studied by participants undertaking prospective estimations cannot be ruled-out.

Ultimately, the present research represents several novel aspects. As the first known VR chronoception study to employ both retrospective and prospective time perception modes, and the first to study chronoception with a commercially available 6DoF VR-specific experience while using a matched-content (VR/non-VR) methodology, it is unsurprising that the findings may diverge from previous studies of both VR and time perception. The results of the study indicate that prospective perception remains significantly more accurate than retrospective perception in VR. While the main effect was significant, the overestimations found indicate that participants' experience, on average, was the opposite of the VR time compression phenomenon that the study aimed to investigate. Consequently, analysis of such results will remain somewhat speculative until supported by further similar studies. At the same time, one outcome from the current study may be of importance to developers and manufacturers of VR experiences. As discussed above, the experience of time distortion in VR is likely to be based on retrospective estimates, given that temporal perception is not typical of VR experiences. The finding that retrospective perception is significantly less accurate than prospective perception suggests that encouraging some awareness of temporal processing in VR experiences may help to mitigate some time distortion effects. As discussed, Wood et al. (2007) found that of the 99% of conventional gamers who had experienced ‘time loss’, 67.5% considered it as sometimes or always a ‘bad thing’. Should similar findings be replicated in VR, inclusion of elements with the capacity to reduce distortion effects is likely to be a welcome development. This represents an avenue for further research, although previous studies suggest that visible and consistent ‘zeitgebers’ such as sun position (Schatzschneider et al., 2016), and accurate experience mechanics replicating expected real-world durations (Bogon et al, 2023) may be effective in addition to clearer temporal cues, such as visible clocks and watches. Experiences which draw attention to temporal processing specifically may also be beneficial. Similarly, experiences which remove or alter aspects of temporal processing may be beneficial in contexts where VR time distortion effects are required, such as in medical distraction therapies. Further research is required to determine whether lack of temporal cues within a VR experience produce commensurate distortion effects to accelerated temporal mechanics associated with the anecdotal temporal ‘warping’ discussed above. Should altered mechanics produce increased levels of retrospective distortion, this could provide increased precision for medical VR interventions.

5.3. Platform Type

The present research found no significant difference in the main effect of ‘platform type’ and no significant interaction between the study factors. As discussed above, in this respect, the present research is commensurate with other studies which have compared HMD and non-HMD in various ways, and which have typically recorded time distortion effects while finding no significant difference between the HMD and non-HMD conditions (Mullen, 2023; Rutrecht et al., 2021; Schatzschneider et al., 2016; Unruh et al., 2021; Van der Ham, 2019). Such results might suggest that there is no meaningful difference to find in time distortion between VR and other forms of digital media. As discussed, despite this VR has been employed in various contexts due to reliable time distortion effects in comparison with other technologies. VR has been found to be effective in alleviating patient symptoms in medical distraction therapy, for example (Schneider et al., 2011; Loreto-Quijada et al., 2014; Chirico et al., 2016). Such uses suggest that there is a meaningful difference between time distortion in VR and other digital technologies, and the lack of significant findings to-date may be the result of limitations in study design.

One of the limitations of previous study designs was the focus on the HMD technology via 'static' experiences, as opposed to the immersive content and control mechanisms. In the present research, the use of a VR-specific 6DoF experience varied from previous studies, and was employed with the aim of ascertaining whether a more VR-specific experience would produce greater time distortion effects in comparison with the 'static' and low-immersion experiences typically used elsewhere. If the non-significant finding in the 'platform type' factor of the present research is related to a limitation of the study design, it may be that the employment of matched-content comparison with the conventional monitor technology is one of the causes.

Matched-content comparison between VR and non-VR in studies is logical because any findings need to be conclusively attributable to VR in comparison with other technologies. To ensure a matched-content methodology the present research included the main effect of 'platform type', and this may have made the design susceptible to similar limitations to those of previous studies. The aim was to investigate the immersive content more specifically by comparing untested 6DoF content between platform types, however in practice this meant that the HMD remained the main VR variable of interest within the study, despite the intended focus on the immersive content. If the immersive content *is* the main VR variable responsible for time distortion effects, in essence the reason for the lack of significant difference between VR and conventional monitor in the present research is that the shared 6DoF content experience meant that all participants were still effectively using VR. In some respects, this is still an informative outcome, as it was useful to examine the principles of prior studies against more VR-specific and higher-magnitude content. The results of the present research may be said to have ruled-out studies examining HMD by comparison with a non-HMD condition using a shared-content methodology, as non-significant results have now been found in studies employing a range of different content-types from 'static' to 6DoF. This suggests an additional trajectory of VR research, as it may indicate that high levels of experience immersion are achievable without HMD technologies, which are often not popular with users for a variety of reasons including comfort, heat, and weight (Yan et al., 2019).

The design of the present study also presented a particular challenge when transposing the VR-specific 6DoF experience into a non-VR context, because accommodations had to be made to allow for the use of the content on a laptop screen, such as participants wearing the HMD on the forehead. While this arrangement worked effectively, it employed an unnatural behaviour which would have represented a limitation of the research, even if a statistically significant result had been found. A conclusion is that future research will need to examine the difference between VR and non-VR conditions by employing immersive content which has been specifically naturalised for the platforms employed. Matched-content study designs may still be possible in this context. Lemmens et al. (2022) tested participants' levels of fear and emotion when playing the horror-survival game *Resident Evil 7* (Capcom, 2017) in both VR and on a conventional gaming platform. While the game was not designed for VR, and reviews of the game in VR suggest a more negative experience compared to playing on a conventional platform which could affect results, the study nevertheless illustrates an approach which could allow for VR/non-VR comparison while focusing on the 6DoF content, and maintaining a more natural and sympathetic user experience.

As a result of these limitations, which may have contributed to the non-significant findings, the present research has not been able to develop understanding of the phenomenon of chronoception-distortion in VR compared to other circumstances and technologies. Additionally, the study has also been unable to provide clarity on the phenomenon of VR time compression, as participants believed they were undertaking the climbing experience for longer than they were on average, in all factors and levels. While time compression is not unique to VR, it has become relatively synonymous with the technology amongst regular users, based on anecdotal reporting (Miller, 2016, Lanier, 2017) and requires further understanding. An anecdotal 'rule of thumb' reported by Miller (2016) is that an hour of time in VR can feel like 15 minutes. While this has not been directly investigated by any known studies, an hour would constitute a 'long duration' according to Vierordt's Law, and underestimations of duration would therefore be anticipated. Studies that have employed similar study durations, such as Walker et al. (2022) who employed a 58-minute interval, have found underestimations of duration commensurate with Vierordt's Law. This is not consistent in gaming, as Rau et al. (2006) found that expert gamers retrospectively underestimated a 60-minute gaming interval, in accordance with Vierordt's Law, while novice players overestimated the same interval. It may be that time compression is also associated with familiarity to a subject, as this would be likely to produce lower levels of stored and retrieved information for retrospective estimation, in-accordance with established research (Block & Zakay, 1997). Regular and expert gamers, familiar with the sensations and experiences of gaming, may experience time compression more readily than novices.

This may be particularly pronounced in VR where the novelty and magnitude of stimulus may be more pronounced than in conventional gaming. As-discussed above, the phenomenon of 'time loss' in conventional gaming has been studied more thoroughly than VR time compression (Nuyens et al., 2020; Wood et al., 2007), and consequently provides a useful point of comparison, as a number of factors including gaming interval length, participants' prior experience, level of immersion, selective allocation of attention, the potential to enter flow states, and the magnitude and novelty of, and emotional response to, gaming stimuli, may all contribute to time loss in conventional gaming, and may also occur (and potentially to an increased amount) in VR. Participants in the present research were predominantly novice users, and the magnitude, novelty, and emotional response to the 6DoF experience may have all contributed to overestimations of duration, which would support such a conclusion. While interval length was not a variable in the present research, and it is consequently not possible to determine whether this may have related to prior VR experience, it may still have been a contributory factor. The interval duration in the present research arguably constitutes a 'short' duration according to Vierordt's Law, and consequently increased inaccuracy would be likely to produce overestimations. Further research is required to determine whether an inversion of this process (i.e. experienced VR users underestimating an interval duration more than novice users) may occur with a longer interval, in-accordance with Vierordt's Law.

Additional factors in VR time compression and time-loss in conventional gaming are the levels of immersion and presence experienced by the participant. As a key platform in the 'immersive technologies' taxonomy, and the technology with the maximal capacity for immersion as indicated by the reality/virtuality continuum (Milgram & Kishino, 1994; Skarbez et al., 2021), the aim of VR is to produce high levels of immersion for a user by limiting visual, and often auditory, sense-contact with stimuli external to the immersive experience. As outlined above, immersion is the level to which an immersive experience can produce this effect, while presence is the level of transportation into the immersive experience that a user may perceive. In accordance with the principle of cognitive absorption, such hyperreal experiences can produce compromised awareness of an external environment.

Users may lose track of where they are in a physical space (contemporary VR systems employ virtual boundary markers as a safety measure to prevent users interacting with an external environment, such as furniture or walls) or experience artificial responses to environmental cues, such as heights, which may be destabilising for some users. Accordingly, level of immersion is likely to be a contributory factor to compromised time perception in VR. Additional analyses using immersion as a covariate showed a violation of regression slopes, so ANCOVA analyses were disregarded. Consequently, the present study cannot support any conclusions relating to levels of immersion. The covariate questionnaire included questions with a 5-point Likert-style scale which may not have been able to identify potentially subtle differences in participant experience of immersion across the study. This may also be a consequence of study design as several participants asked for clarification on the meaning of immersion when answering the related questionnaire item, suggesting unfamiliarity and potentially varied interpretations of the term. While this is to be expected, based on the discussion above, it still represents a limitation of the present study. Future research will need to ensure consistency in ascertaining levels of immersion, and potentially ensuring clarity of the term among participants, if studies involve self-reporting elements relating to immersion.

One of the leading theories for time loss in gaming relates to self-awareness (Nuyens et al. 2020), and the associated connection with flow states (Csíkszentmihályi, 1975) in which an individual becomes completely involved in a task that matches their skill level to an equivalent level of challenge, such as may be found in gaming. An individual experiencing a flow state is likely to be concentrating attentional resources on the task in hand, to the extent of experiencing potential loss of self-awareness during the task interval. As discussed, flow states seem to occur differently in VR than in conventional gaming. Lemmens and von Münchhausen (2023) found that users in VR did not experience boredom when a game experience was too easy, and when the game was excessively difficult VR users were considerably more prone to frustration. The equilibrium point of optimum balance between challenge and reward required for a flow state may be lower for VR users (closer to the 'easy' end of a challenge continuum) than in conventional gaming, with VR users more susceptible to frustrations from difficulty, and less susceptible to boredom when an experience was insufficiently challenging. Combined with the principles of cognitive absorption relating to digital technologies, whereby participants may experience temporal dissociation simply from a level of interaction with the technology (Agarwat & Karahanna, 2000), this could suggest that time distortion in VR may involve only low levels of interaction and challenge.

Such findings may be reflected in the present research. Based on the potential for high-magnitude and novel stimuli discussed earlier, it is probable that participants in the study were not able to enter into a flow state. Firstly, given the seemingly different point of equilibrium indicated by Lemmens and von Münchhausen (2023), the challenging aspects of the stimulus may have placed participants outside of the 'flow channel' between skill-level and challenge (Csíkszentmihályi, 1993). Achievement of a flow state requires a delicate balance between various factors (Rau et al., 2006) in addition to arousal and boredom, including anxiety and relaxation, and worry and control. The magnitude and novelty of stimulus and destabilising effects of the climbing experience which have been associated with increase in affective states (Estupiñán et al., 2014), as well as the knowledge of taking part in a study, suggest that such a balance may have been unlikely for participants new to *The Climb II* in all cases, and VR itself for many participants. However, the current questionnaire did not include a direct question relating to flow states, so no conclusions can be drawn in the present research. Consequently, while participants achieving a flow state during the study task cannot be ruled-out, a conclusion that all participants were experiencing some form of arresting and novel stimulus, and unable to achieve a balanced flow-state during the study, seems not unlikely. Given that flow states are associated with gaming and immersion, and are also responsible for time loss, the inability of participants to achieve a flow state means that the experience of participants within the present research was not necessarily commensurate with that of the typical VR user, and this consequently represents a limitation of the present study. Further studies will be needed to examine VR use scenarios more typical of home users, and as discussed above, in addition to including more robust measures of flow state, prior VR experience, and immersion, will also need to employ longer interval durations, and some metric of success upon which to base them. Without such measures, studies will not be able to replicate the range of conditions relating to VR time compression required for more complete understanding of the phenomenon.

5.4. Additional Study Limitations

While key limitations of the present research have been discussed above, there are several further limitations which are expedient to a broader analysis of findings. This is because of the two key novel components; the comparison of time perception modes and the inclusion of commercially available, VR-specific 6DoF content in a matched-content study. Both elements are - as far as is known - unique to this study and represent an attempt to provide a new trajectory of research progression within the field of VR chronoception studies. Novel components in any system are unpredictable; while they may have been tested and developed in other contexts, how they will interact with other aspects of a new system cannot always be accurately predicted. Accordingly, the inclusion of these untested aspects of the study design equated to challenges in predicting the outcomes of the study, and to interpretation of the data. Consequently, although a further analysis of the research reveals various limitations of the study design and assessment metrics, these could only be known a posteriori.

As discussed, matched content (VR/non-VR) studies are a benchmark of good practice in VR research. Numerous studies have successfully illustrated the need for a clear demarcation between VR and non-VR, although only two previous studies, Mallam et al. (2020) and Lemmens et al. (2022) are known to have used commercially-available 6DoF content. While significant results were achieved in both studies, they did produce anomalies. Lemmens et al. used horror game *Resident Evil 7* (Capcom, 2017) which did not transition well to VR (reviews included degraded graphics and awkward user-interface mechanics; The Verge, 2017) which made a like-for-like comparison harder in test conditions. Mallam et al. reported that participants demonstrably learned the study task more easily in the non-VR condition, which the study authors attributed to difficulties some participants had in navigating the experience (designed for conventional screens) in VR.

While these studies employed non-VR content in VR conditions, the present research attempted the opposite; to present VR-specific content in a non-VR condition. While the user interface mechanics worked effectively, participants reported similar effects to those reported by Mallam et al., (2020) only in reverse. Where participants in that study found navigating the conventional monitor experience challenging in VR, participants in the present study experienced challenges navigating the VR experience on a conventional screen. Aside from the fixed position of the laptop screen, which necessitated participants needing to recalibrate their view to see more oblique angles, participants also found the non-VR condition in the present study to be quite taxing, as their spatial realism was reduced due to the visible hands on the laptop screen not being positioned where their actual hands were in 3D space. Participants consequently needed to be more deliberate about the placement of their hands on the virtual rock face, as they were only able to approximate where their hands were in relation to it. Conversely, participants in VR experienced no such difficulties as their virtual hands were analogous with the position of their real hands. All conventional monitor participants were invited to try the experience in VR afterward in non-test conditions. Every participant took-up this opportunity, and while it was not recorded officially due to being outside test conditions, participants consistently confirmed that the experience in VR was much easier, although some participants still preferred using the conventional monitor. Such deliberate actions in the non-VR condition may perhaps suggest that allocation of attentional resources and/or cognitive load may have been increased due to the difficulty of the experience. While this is not supported by related questionnaire items due to non-significant findings and rejection of ANCOVA analyses, the potential effect this might have had on time perception in the non-VR condition cannot be ruled out. This also illustrates again the need for a success metric in the study to determine variations between the VR and non-VR conditions. The lack of a significant difference in estimate accuracy between the two conditions does not rule-out the possibility that the experience was more challenging in the non-VR condition, as such a difference would be important to an accurate interpretation of findings.

An unusual anecdotal finding from the study was the development of two quite distinctly different experiences of the climbing simulator, which was not anticipated and not looked for until a pattern began to emerge. Consequently, the data cannot be clarified because early participants in the study were not asked about this experience. Of those participants who were asked (approximately three-quarters of participants) roughly half felt themselves to be moving *through* the virtual environment (i.e. climbing on a static mountain as normal) while the other half experienced a sensation that *they* themselves were static, and that it was the environment which was moving. These participants felt that they were effectively ‘dragging’ (and even ‘throwing’) the environment around themselves. This did not appear to be connected to platform type, as participants in both VR and conventional monitor groups seemed equally likely to report either experience, and while this did not constitute part of the study therefore, it represents another avenue for further studies.

Variations in subjective experience within VR are not uncommon. Lanier (2017) reported that subjective user experiences varied even in the earliest iterations of the technology. Lanier's first VR experiences in the 1980s were designed to produce artificial 'God-like' sensations for the user, who would be able to manipulate the entire environment around themselves. By contrast, contemporary VR experience-design tends toward a reproduction of a more tangible 'reality'. Such variations in participant experience - some experiencing a more normalised simulation of a real-world activity, and others experiencing a more 'God-like' control and manipulation of an environment – may have affected the perceived duration of the experience, and conceivably may have contributed to the level of immersion and connection to the experience. In this context, including only one item relating to immersion in the post-study questionnaire is a limitation of the study design. More specificity was needed to fully understand and analyse the experience of immersion and its relationship to recorded duration estimates. This also relates to flow states because the limited understanding of immersion levels within the study also means that participants' proximity to achieving a flow state cannot be estimated. This makes the study difficult to compare with studies of conventional gaming, and it remains unclear whether VR gaming produces commensurate or different levels of chronoception-distortion to conventional gaming. Future studies of VR chronoception should consequently employ some clear and repeatable measure of flow state, such as the Experience Sampling Method (ESM) (Larson & Csíkszentmihályi, 2014) or Jackson and Marsh's (1996) four-item flow scale for time perception. For this study, even the Flow Short Scale (Rheinberg et al., 2003) which includes only a single item ('I don't notice time passing') would have been a useful addition to the post-study questionnaire.

Finally, while a case has been presented for the immersive content being the primary VR variable responsible for time distortion effects, the varied subjective experience of participants may also point toward the tangible control mechanisms employed. Participants who felt that they were 'moving' and 'throwing' the environment around themselves may not have felt such a sensation (or to the same extent) if the experience had been controlled by a conventional control system such as a games console controller, which did not need to move in 3D space, and which was not analogous to participants' own hands. Research examining VR control mechanisms is limited to-date, although studies such as Palombo et al. (2024) have found that control mechanisms affect cognitive absorption levels in VR, and consequently this is an area of VR research which requires further development. If such variations of experience are demonstrated by further research to be due to control mechanisms, such a finding would be of importance to VR design, as technologies and/or experiences could be designed to avoid such unnatural effects, or potentially to enhance them for certain experiences if required.

Chapter Six. Conclusion.

The research has shown that distortions in time perception while using VR are more pronounced when estimates are made retrospectively. As temporal awareness is not normally a prerequisite of VR experiences, the typical experience of VR time distortion is that it is likely to occur retrospectively. Accordingly, more could potentially be done by developers and manufacturers of VR technologies and experiences to introduce temporal awareness within experiences, to mitigate time distortion effects in circumstances where they are not required. Conversely, in experiences where time distortion is a goal, such as in medical distraction therapies, experiences specifically designed to avoid temporal associations may be more efficacious. Prospective estimations in the research were still found to be distorted however, and the study has identified various contexts in which further research is required, to understand the phenomenon more specifically.

Importantly, the research found overestimations of duration in all factors and conditions, which is oppositional to the anecdotal reporting of VR time distortion as typically being a form of time compression. In doing so, the research is commensurate with previous studies of the phenomenon which have typically found overestimations, and time distortion effects with no difference between VR and non-VR conditions. VR is an emergent technology, and VR time perception is not a thoroughly studied field, so that conclusions within the research cannot be measured against a large body of established knowledge, and must therefore be tentative at best. A consistent outcome from the research and prior studies is the finding of time distortion effects without any evidence linking them specifically to VR. As studies to-date have concentrated on the HMD technology against a range of content types, from 'static' experiences to the 6DoF content in the current study, the attribution of time distortion effects to the immersive content employed, rather than the VR hardware, is just such a tentative conclusion from the research.

This study included a number of novel features, and contributes to the developing body of knowledge surrounding VR time perception by verifying findings and outcomes from prior research in previously unstudied contexts. The finding of significant retrospective inaccuracy and consequent distortion in VR compared to prospective accuracy may be of importance to developers, as the inclusion of more specific temporal cues and mechanics within devices and experiences may help to mitigate some aspects of chronoception-distortion, or indeed to enhance them for scenarios such as medical therapies. The inclusion of commercially available, VR-specific 6DoF content in the present research, and both time perception modes, offered both new perspectives, and (perhaps more usefully) have determined a number of further areas for research.

The limitations in the current study found by transposing VR-specific content onto a non-VR platform provides context for further research by determining that VR and comparison technologies require naturalised content in order to make meaningful comparisons. Varied and longer interval durations are also likely to contribute to research which more accurately recreates a typical VR experience. More needs to be done to understand contributory factors in studies, such as prior VR experience, levels of immersion and flow, and anecdotal reporting of potentially VR-specific effects, such as temporal 'warping' and the perception of accelerated mechanics. Studies such as Nuyens et al (2020) who found regular gamers exhibited impaired perception compared to non-gamers when aroused by gaming stimuli require examination in VR, and connected to this, the potential for VR time compression to be associated with prior VR experience due to stimulus magnitude and novelty also requires study. Further VR studies are required which include success metrics for more nuanced analysis, and specifically metrics which generate a measurable interval, rather than employing an abstract duration. Variations also need to be considered between time perception modes, as the current research has identified circumstances in which both prospective and retrospective paradigms may not apply to VR chronoception as accurately as in real-world contexts. The findings of Bogon et al. (2020) that VR does not alter time perception also require verification, as this may be the case but only in prospective perception.

Finally, the current study is commensurate with a number of other VR chronoception studies which have found distortion effects with no difference in platform type. A consequent conclusion is that chronoception-distortion in VR may be more likely to be caused by the immersive content employed, rather than the HMD technology. Such a conclusion requires verification, as it could have potentially wide-ranging consequences for VR developers, manufacturers, and users.

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Appendix.

Appendix 1: Participant Information Form.

Time perception in Virtual Reality – MScR Research Project.
Participant Information Form.

Name of Principal Investigator: James Dalby

Title of Research: An investigation of psychological effects while using virtual reality technologies.

Aim of Research: To investigate psychological effects of using virtual reality technologies compared to conventional computer monitors.

Description of Procedure: You will be asked to undertake a virtual rock-climbing experience either in virtual reality or using a conventional computer monitor, and afterwards you will be asked a short series of questions about your experience, and also to complete a short questionnaire about certain aspects of your session, such as how immersed you felt during the experience.

You may find the virtual rock-climbing experience to be very realistic, and an important part of this is that you are able to 'fall' within the experience, which may be disconcerting or uncomfortable. Falling is not a guaranteed part of the experience but it will occur if you either 'let go' or make a mistake while climbing. You will be invited to undertake a practice period of climbing within a basic level before the test begins.

You can stop your participation at any point by simply signalling to the researcher, who will remain present throughout, that you would like to stop.

Description of Risks: The virtual reality experience may make you feel uncomfortable due to the perception of climbing and heights, as well as other occasional effects from the technology such as vertigo or nausea, but aside from these (usually mild) effects, there are no expected risks with the study.

Data Collection and Storage: Please read the University's standard Privacy Notice (http://www.glos.ac.uk/docs/download/Privacy-notices/Research-Participants-Privacy-Notice.pdf). All data will be dealt with in accordance with data protection legislation. Data from the study and questionnaire will be collected by hand, and converted to a digital format where it will be stored on a password-protected folder on the University's OneDrive system. All data will be anonymised such that individual participants will not be personally identifiable from their data, with consent forms, questionnaires, and other data being completed on a computer, and stored separately on a secure, password protected file which will be permanently deleted

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once the grade has been confirmed at the exam board. This anonymised data set may be published alongside any subsequent journal article or other publication.

Right to withdraw: You have the right to withdraw your data at any time during the study (simply by stopping the climbing task or not answering any question you do not feel comfortable answering) and up to two weeks after participation. Before you undertake the study, you will be asked to create a unique participant code. If you decide to withdraw your data after you have taken part, all you will need to do is email me, providing me with your code within two weeks of participation.
Contact information: If you have any questions about the research, or wish to know any more details, please contact James Dalby at jdalby@glos.ac.uk.

If you have any questions about the conduct of the research, please contact the supervisor: Kerry Rees krees@glos.ac.uk.

If you have any questions about the ethics of the research, please contact the Chair of the Research Ethics Panel: Dr Danielle Stephens-Lewis, dstephenslewis@glos.ac.uk.

This research has been approved by the Psychological Sciences Research Ethics Panel.

Appendix 2: Participant Consent Form.

Time perception in Virtual Reality – MScR Research Project.
Participant Consent Form.

Your data will be stored securely and confidentially. In order that we may retrieve your data should you wish to withdraw; you will be asked to provide a unique identifier that will be used to label any-and-all materials relating to your participation in this study. You will need to provide your identifier (this is detailed on the next page) should you wish to withdraw from the study, which we would ask that you do within two weeks of taking part. Any requests to withdraw after this time may not be actionable as the data will already be anonymously entered for analysis.

1. I have read the information sheet provided and understand what I am required to do in order to take part in this study.

2. I have been advised of my rights as a participant and understand that I can withdraw my data from this research project at any time, without giving a reason.

3. I have had the opportunity to ask questions before consenting to participate in the study and am satisfied with the information provided either through the information sheet, or from adequately answered questions to the researcher.

4. I understand that any data I provide will be kept securely and no material will be published which will identify me personally.

5. I confirm that I am over 18 years old; that I consent to allowing the answers I provide to be included in the analysis and reporting of the study, including potential publication; and that there is no reason why I consider myself unable to take part.

6. I understand that I will be asked to undertake a virtual rock-climbing experience which may include uncomfortable sensations, such as 'falling'.

7. I understand that I may be asked to undertake this experience using virtual reality technology, which may also present certain documented effects, including disorientation, fatigue, vertigo, motion sickness, and potentially seizures in users with epilepsy. By continuing with this test, I confirm that I am aware of these potential effects.

8. I confirm that if I have experienced any negative effects from virtual reality in the past, or if I suffer from epilepsy, headaches, motion sickness or balance problems, or if I am pregnant, I will inform the researcher prior to the test, and may be asked either to withdraw my participation, or to undertake the test on the conventional monitor rather than in virtual reality.

9. I understand by ticking the box below that I am confirming my consent to take part in this research.

Your Unique Identifier (UI).
Below, please create a Unique Identifier using the first three letters of a memorable name (such as Mother's Maiden Name) and the first four digits of your date-of-birth. For example, Jones and 01/01/1990 would become JON0101.

Confirmation and Consent.

1. **Please provide your:**

a. Name:	
b. Contact email:	
c. Date of Birth:	
d. Unique Identifier (see above):	

2. **Please tick this box to confirm that you have read and understood the points above, and to give your consent to proceed:** ☐

If you have any questions about the research, please contact the researcher: James Dalby at jdalby@.glos.ac.uk. If you have any questions about the conduct of the research, please contact the supervisor: Dr. Kerry Rees, krees@connect.glos.ac.uk. If you have any questions about the ethics of the research, please contact the Chair of the Research Ethics Panel: Dr. Danielle Stephens-Lewis, dstephens-lewis@glos.ac.uk.

This research has been approved by the Psychological Sciences Research Ethics Panel.

Appendix 3: Participant Debrief Form.

Time perception in Virtual Reality – MScR Research Project.
Participant Debrief Form.

Thank you for your contribution to this research. In this study I am looking at time perception in virtual reality, and the potential for time-distortion when using the technology compared to more conventional computer monitors. You can read more about this subject in the article 'You Perceive Time Differently in Virtual Reality, Scientists Say' by Tangerman, 2021.

We perceive time differently depending on whether it is prospective or retrospective; for example if someone asks you to do something in 5-minutes time you have a starting point and can judge the passage of time accordingly, whereas if someone asks you how long ago something occurred, all you have to draw upon is your memories during that time. I'm interested in how these processes work in virtual reality, so some participants in this study have been tested on prospective timing, and some on retrospective timing. To illustrate how this process might work specifically in virtual reality, half of the participants in this study have been tested using a conventional computer monitor so that we can see any differences between the experience of time while using the two technologies.

You have the right to withdraw your confidential data from the study up to two weeks after the date of your participation. To withdraw your data, please email jdalby@glos.ac.uk with your unique participant identifier and simply state that you no longer wish for your data to be included in the research. Your involvement will remain confidential at all times, and your data will be anonymous throughout.

Should you experience any lasting discomfort after undertaking this test, please contact your GP, and should the experience of climbing and/or falling trigger any form of upset, please contact:

Mind (Mental Health charity) - 0300 123 3393 (www.mind.org.uk)
Samaritans – 166 123 (www.samaritans.org)

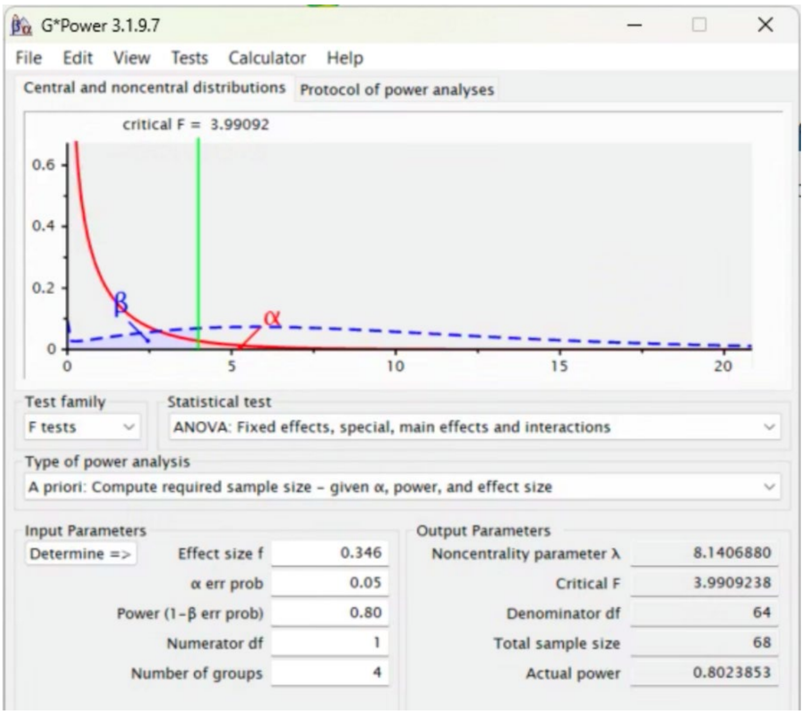
If you have any questions about the research, please contact the researcher: James Dalby at jdalby@glos.ac.uk. If you have any questions about the conduct of the research, please contact the supervisor: Dr. Kerry Rees, krees@connect.glos.ac.uk. If you have any questions about the ethics of the research, please contact the Chair of the Research Ethics Panel: Dr. Danielle Stephens-Lewis, dstephens-lewis@glos.ac.uk..

This research has been approved by the Psychological Sciences Research Ethics Panel.

Appendix 4: Illustration of HMD mounting for conventional monitor users.

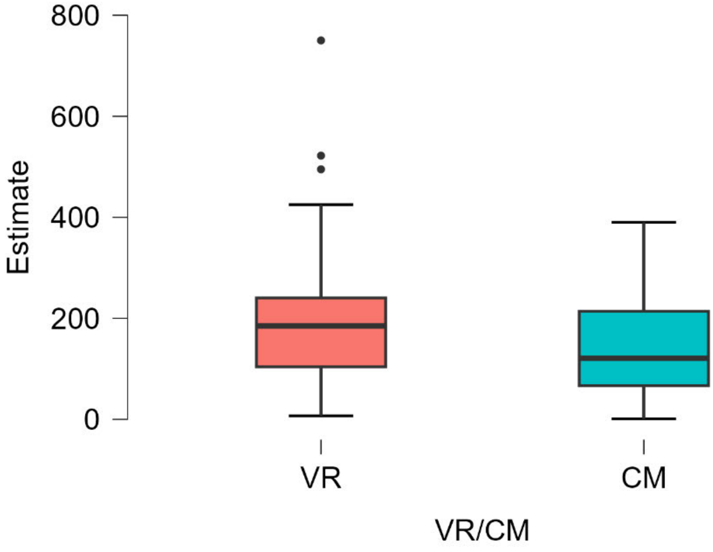
Visible is Oculus Quest 2 HMD and boboVR M2 PRO+ cantilever system used with all participants.

Appendix 5: Illustration of pre-test power analysis using G*Power.

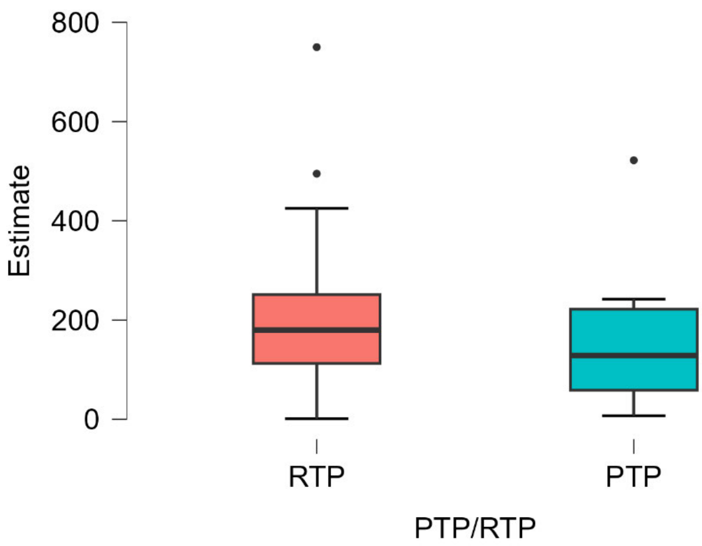


Appendix 6: Box plots illustrating outliers. VR= Virtual Reality. CM= conventional monitor. PTP= prospective time perception. RTP= retrospective time perception.

Outliers by Platform Type



Outliers by Time Perception Mode



Appendix 7: Data table. Estimates column illustrates the variance of each estimate from the target duration of 510 seconds.

	Estimate (secs)	VR/CM	Retrospective/Prospective
1	290	VR	RTP
2	180	VR	RTP
3	190	VR	RTP
4	410	VR	RTP
5	40	VR	RTP
6	190	VR	RTP
7	425	VR	RTP
8	174	VR	RTP
9	255	VR	RTP
10	415	VR	RTP
11	60	VR	RTP
12	235	VR	RTP
13	190	VR	RTP
14	120	VR	RTP
15	110	VR	RTP
16	67	VR	RTP
17	102	VR	RTP
18	229	VR	PTP
19	241	VR	PTP
20	12	VR	PTP
21	30	VR	PTP
22	110	VR	PTP
23	242	VR	PTP
24	7	VR	PTP
25	238	VR	PTP
26	47	VR	PTP
27	121	VR	PTP
28	179	VR	PTP
29	136	VR	PTP
30	223	VR	PTP
31	239	VR	PTP
32	136	VR	PTP
33	100	VR	PTP
34	204	VR	PTP
35	92	VR	PTP
36	180	CM	RTP
37	240	CM	RTP
38	1	CM	RTP
39	122	CM	RTP
40	80	CM	RTP
41	180	CM	RTP
42	174	CM	RTP
43	90	CM	RTP
44	120	CM	RTP
45	240	CM	RTP
46	390	CM	RTP
47	347	CM	RTP
48	120	CM	RTP
49	240	CM	RTP
50	65	CM	RTP
51	199	CM	PTP
52	66	CM	PTP
53	99	CM	PTP
54	219	CM	PTP
55	107	CM	PTP
56	149	CM	PTP
57	142	CM	PTP
58	56	CM	PTP
59	21	CM	PTP
60	32	CM	PTP
61	242	CM	PTP
62	46	CM	PTP
63	31	CM	PTP
64	68	CM	PTP
65	230	CM	PTP

Appendix 8. JASP output.

ANOVA - Estimate (secs)

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
VR/CM	14719.752	1	14719.752	1.490	0.227	0.024
Retrospective/Prospective	56449.711	1	56449.711	5.713	0.020	0.086
VR/CM ✻ Retrospective/Prospective	1.711	1	1.711	1.731×10^{-4}	0.990	2.839×10^{-6}
Residuals	602693.765	61	9880.226			

Note. Type III Sum of Squares

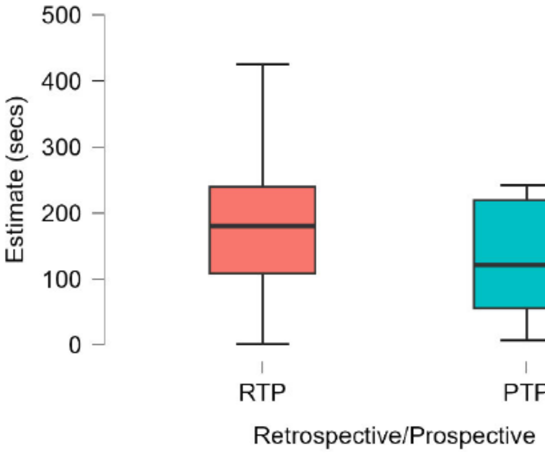
Descriptives - Estimate (secs)

VR/CM	Retrospective/Prospective	N	Mean	SD	SE	Coefficient of variation
CM	PTP	15	113.800	77.939	20.124	0.685
	RTP	15	172.600	105.537	27.250	0.611
VR	PTP	18	143.667	84.092	19.821	0.585
	RTP	17	203.118	122.858	29.797	0.605

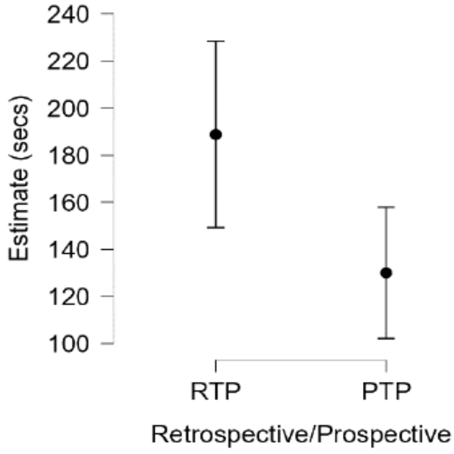
Descriptive Statistics – Time Perception Mode

	Estimate (secs)	
	RTP	**PTP**
Valid	**32**	**33**
Missing	**0**	**0**
Mean	**188.813**	**130.091**
Std. Error of Mean	**20.202**	**14.187**
95% CI Mean Upper	**230.015**	**158.990**
95% CI Mean Lower	**147.610**	**101.192**
Std. Deviation	**114.280**	**81.501**
Minimum	**1.000**	**7.000**
Maximum	**425.000**	**242.000**

Boxplot for Time Perception Mode

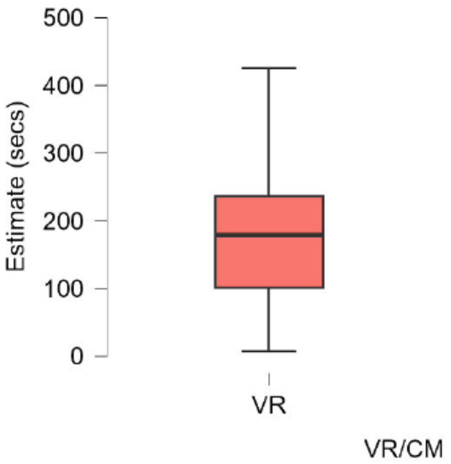


Interval Plot for Time Perception Mode

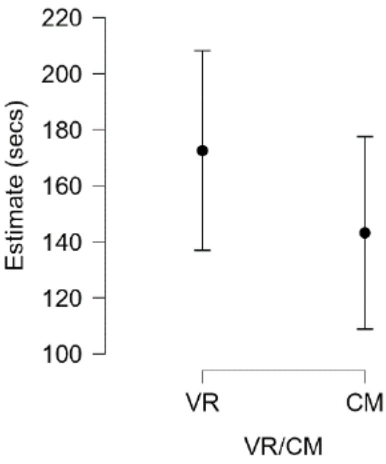


Descriptive Statistics – Platform Type	Estimate (secs)	
	VR	CM
Valid	35	30
Missing	0	0
Mean	172.543	143.200
Std. Error of Mean	18.164	17.515
95% CI Mean Upper	209.457	179.023
95% CI Mean Lower	135.629	107.377
Std. Deviation	107.460	95.936
Minimum	7.000	1.000
Maximum	425.000	390.000

Boxplot for Platform Type



Interval Plot for Platform Type



Appendix 9. Additional data visualisations.

Error bar chart illustrating estimate means and 95% confidence intervals.

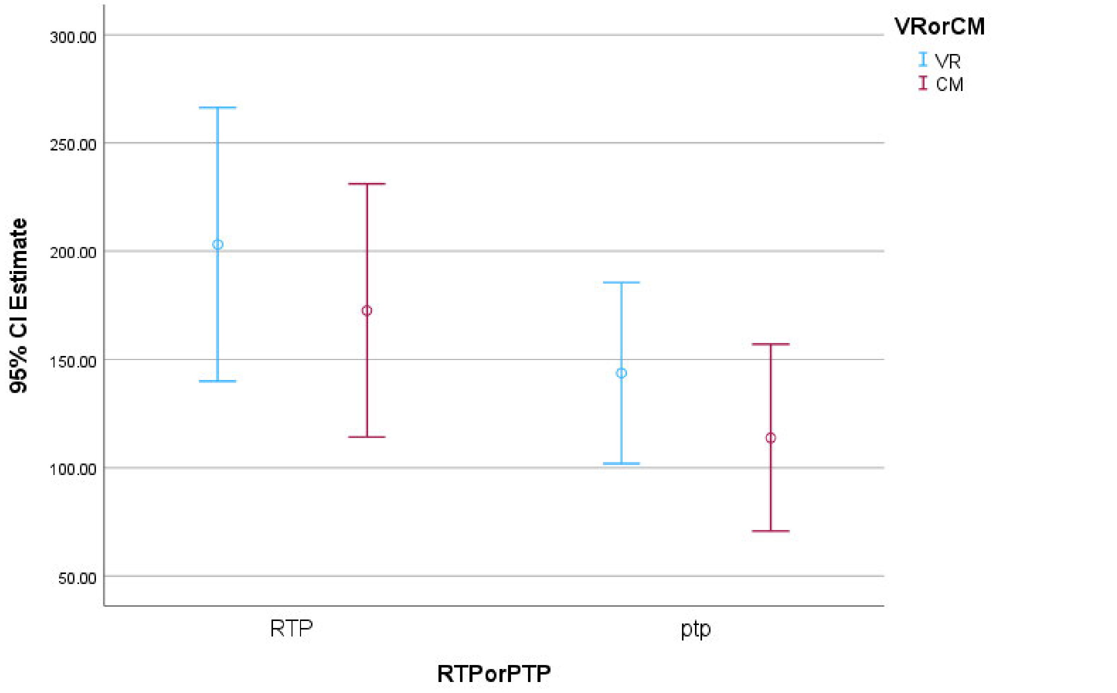


Illustration of non-significant interaction between factors.

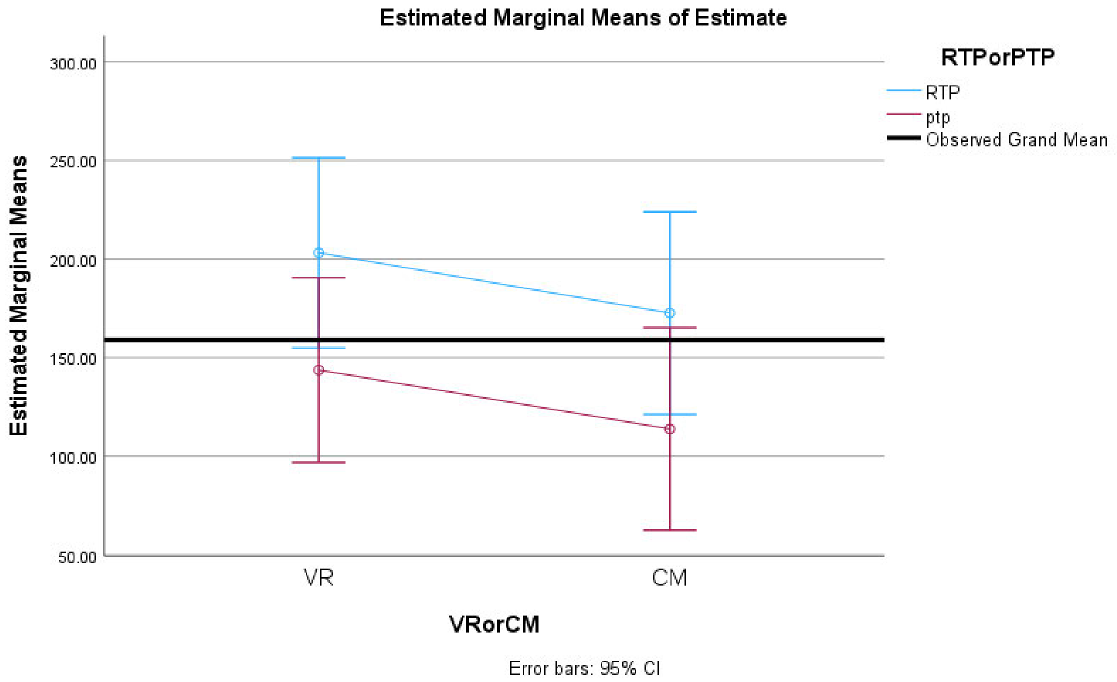


Illustration of estimate means and confidence intervals for Platform Type.

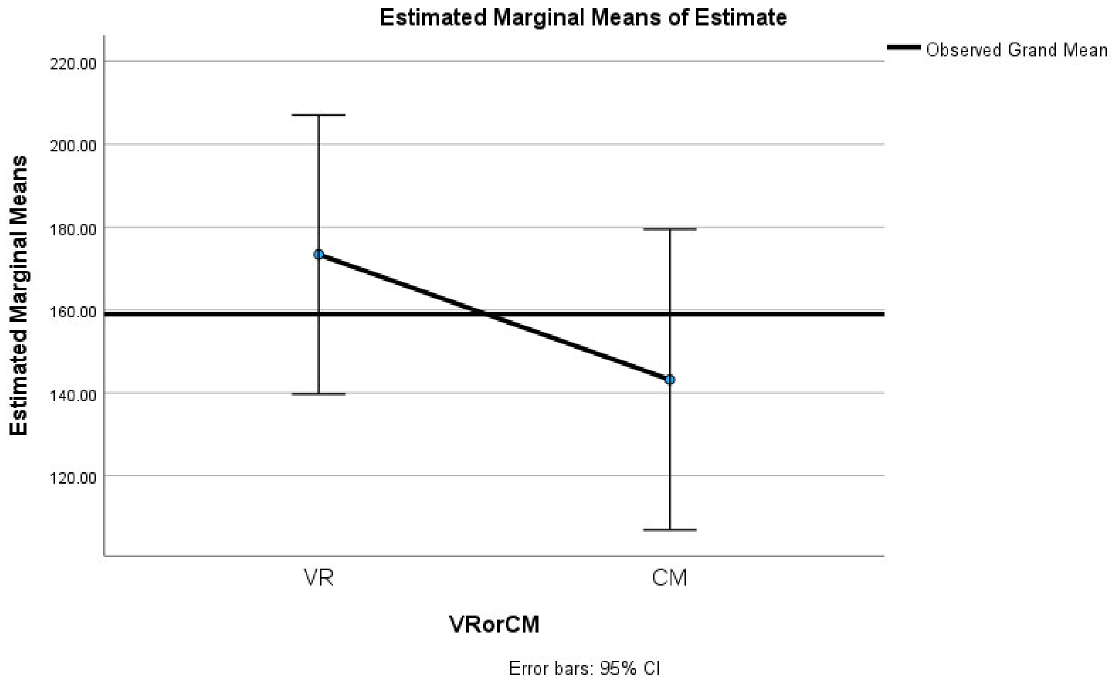
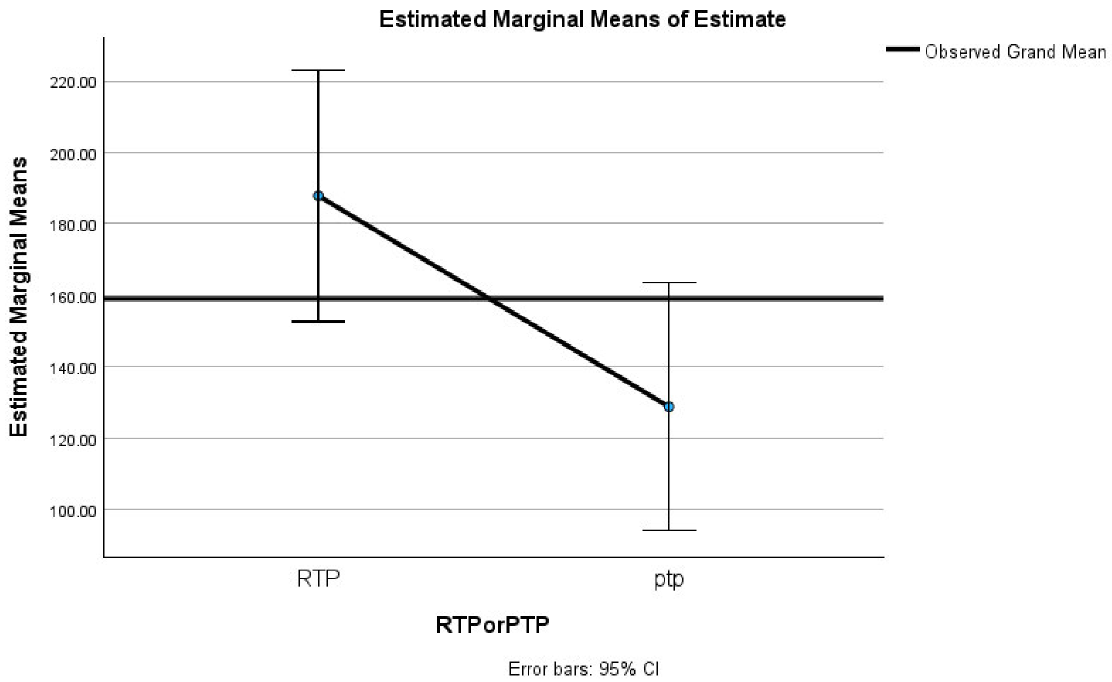


Illustration of estimate means and confidence intervals for Time Perception Mode.



Appendix 10. Example of online discussion of ‘warp’ functionality in *American Truck Simulator* (SCS Software) on the *Steam* platform (Valve). Discussion dated July 2024, accessed 28/09/2024 from
https://steamcommunity.com/app/270880/discussions/0/4418677017729367171/

Reese 9 Jul @ 10:56pm

There is a config setting called "warp." Warp controls the flow of time, which affects all things such as physics, light timings, day/night cycle, etc. The default is 1, which is a little high. 0.79-0.92 is generally known to be the more factual setting.

This experience you have could also be caused by a mod. Does this experience also apply when not in VR?

#1

VRtuous 9 Jul @ 10:58pm

A warp of 1 would mean the game is janky and sped up ???!

#2

DarkEternal 9 Jul @ 11:02pm

> *Originally posted by* ***VRtuous***:
> A warp of 1 would mean the game is janky and sped up ???!

No, they said the DEFAULT is 1. As in, the game itself was designed around "Warp = 1".
It is supposed to be normal (default) speed. Some players lower it to better match the real world.

Last edited by DarkEternal; 9 Jul @ 11:03pm

#3

VRtuous 9 Jul @ 11:06pm

So it IS sped up by default relative to the real world !
I think it is the case because I tried it in desktop right this moment and it look a bit sped up indeed but not quite as much as in VR.

I haven't found this "warp" setting thought. Where is it ?

#4

Wolfgang 9 Jul @ 11:25pm

With the map and time scale being 1:20 the time in the game is of course sped up. You would do a mile per second IRL either, just saying.

#5

Reese 9 Jul @ 11:56pm

I'm saying the default is 1 and that you might have artificially increased it, either on purpose and forgot about it or accidentally. It is not an in-game setting. It is a config.cfg setting in the Documents/American Truck Simulator/Profiles/<your profile>/config.cfg

For 99% of players, a warp of 1 will look fine. 1 does not look that far out of place.

#6

Komfr [developer] 10 Jul @ 12:55am

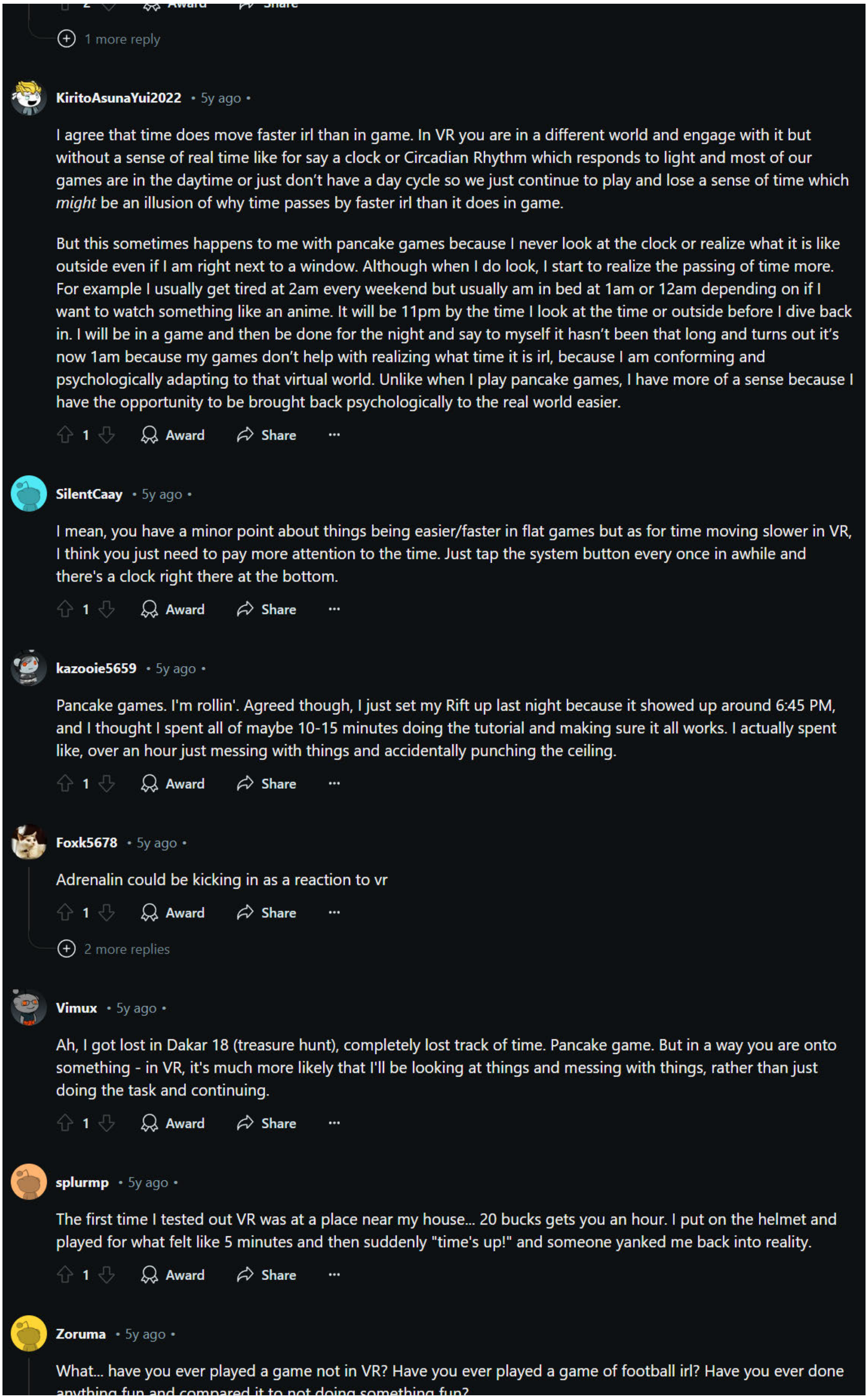
Go to the config.cfg and ensure that t_locked_fps is set to 0

#7

VRtuous 11 Jul @ 5:26pm

> *Originally posted by* ***Reese***:
> I'm saying the default is 1 and that you might have artificially increased it, either on purpose and forgot about it or accidentally. It is not an in-game setting. It is a config.cfg setting in the Documents/American Truck Simulator/Profiles/<your profile>/config.cfg
>
> For 99% of players, a warp of 1 will look fine. 1 does not look that far out of place.

Appendix 11. Example of online discussion of temporal acceleration in VR on the *Reddit* platform. Discussion dated 2019, accessed 28/09/2024 from https://www.reddit.com/r/virtualreality/comments/e70kk1/time_perception_is_slower_in_vr/



1 more reply

KiritoAsunaYui2022 • 5y ago •

I agree that time does move faster irl than in game. In VR you are in a different world and engage with it but without a sense of real time like for say a clock or Circadian Rhythm which responds to light and most of our games are in the daytime or just don't have a day cycle so we just continue to play and lose a sense of time which *might* be an illusion of why time passes by faster irl than it does in game.

But this sometimes happens to me with pancake games because I never look at the clock or realize what it is like outside even if I am right next to a window. Although when I do look, I start to realize the passing of time more. For example I usually get tired at 2am every weekend but usually am in bed at 1am or 12am depending on if I want to watch something like an anime. It will be 11pm by the time I look at the time or outside before I dive back in. I will be in a game and then be done for the night and say to myself it hasn't been that long and turns out it's now 1am because my games don't help with realizing what time it is irl, because I am conforming and psychologically adapting to that virtual world. Unlike when I play pancake games, I have more of a sense because I have the opportunity to be brought back psychologically to the real world easier.

1 Award Share ···

SilentCaay • 5y ago •

I mean, you have a minor point about things being easier/faster in flat games but as for time moving slower in VR, I think you just need to pay more attention to the time. Just tap the system button every once in awhile and there's a clock right there at the bottom.

1 Award Share ···

kazooie5659 • 5y ago •

Pancake games. I'm rollin'. Agreed though, I just set my Rift up last night because it showed up around 6:45 PM, and I thought I spent all of maybe 10-15 minutes doing the tutorial and making sure it all works. I actually spent like, over an hour just messing with things and accidentally punching the ceiling.

1 Award Share ···

Foxk5678 • 5y ago •

Adrenalin could be kicking in as a reaction to vr

1 Award Share ···

2 more replies

Vimux • 5y ago •

Ah, I got lost in Dakar 18 (treasure hunt), completely lost track of time. Pancake game. But in a way you are onto something - in VR, it's much more likely that I'll be looking at things and messing with things, rather than just doing the task and continuing.

1 Award Share ···

splurmp • 5y ago •

The first time I tested out VR was at a place near my house... 20 bucks gets you an hour. I put on the helmet and played for what felt like 5 minutes and then suddenly "time's up!" and someone yanked me back into reality.

1 Award Share ···

Zoruma • 5y ago •

What... have you ever played a game not in VR? Have you ever played a game of football irl? Have you ever done anything fun and compared it to not doing something fun?

Appendix 12. Example of online discussion of time perception and immersion in VR on the *Reddit* platform. Discussion dated December 2023, accessed 28/09/2024 from https://www.reddit.com/r/singularity/comments/18673rh/can_perceived_time_be_extended_in_a_fulldive/

IWasSapien • 10mo ago •

It's possible if you increase number of events in a time period, literally what computers are doing

2 Reply Award Share ···

RabidHexley • 10mo ago • Edited 10mo ago •

My hypothesis is that all that can really be done is modifying our perception of "big time". Kind of how in real current games in-game days pass fairly quickly, it might be possible to give players the illusion of actual days passing over the course of a few hours, like a dream.

The above is mostly about influencing the retroactive perception of time, which is highly variable under normal circumstances. But, I don't think there's any indication- given what we know currently, which may always change - that it would be possible to *truly* compress time. Where we could actually cram 4 hours worth of "stuff" into a 1 hour period. Merely that we could make a player doing 1 hour of stuff *feel* like 4 hours (or days, or whatever).

The main thing is that it would be an illusion, the player can't actually do more stuff in the same amount of time. This might not matter for gameplay purposes though, since real-life isn't a game and is full of boring minutia we barely remember, it'd be like a tv show that takes place over years but only the interesting bits are actually shown.

1 Reply Award Share ···

helliun • 10mo ago •

or infinite torture chambers

1 Reply Award Share ···

Chmuurkaa_ • 10mo ago •

Ever smoked weed? If a plant can make me feel like an hour has passed just to look at the clock and see that it has only been 12 minutes then I'd be really surprised if that can't be reproduced artificially

3 Reply Award Share ···

BadgerOfDoom99 • 10mo ago •

Well your perception of time can certainly alter but it's not clear that your brain itself can go any faster. You might feel that extra time passed but not actually achieve anything that would take equivalent real time. So you could not learn perfect french in a couple of hours even if you could be tricked into having memories of a trip to Paris. Maybe that would be enough for a game, like FPS, you could pick a resolution/time for how detailed each day would be.

1 Reply Award Share ···

trynothard • 10mo ago •

Depends on if we understand memories and how to control/create and implant new ones.

As for actually forcing the brain to process a years worth of data in a few minutes might just simple melt your head.

1 Reply Award Share ···

BrilliantResort8146 • 10mo ago •

"where's the device that speeds or slows down the passage of time?" Professor Farnsworth "under the seat" Orange Joe lol

3 Reply Award Share ···

NormalEffect99 • 10mo ago •

Yes, this will be our civilizations endgame and is the answer to the femi paradox. Fdvr immortality.