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Can Time Flow Differently if You Are a Virtual Reality Newcomer?

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Abstract

Virtual Reality (VR) technologies have entered many aspects of daily life (e.g., workplace, education, gaming). VR users report that time flows faster when immersed in a virtual environment. Such an effect is supported by recent scientific evidence (Mullen & Davidenko, 2021). Indeed, a familiarity effect could foster such a time compression effect. To investigate this possibility, a between-subject design was adopted: in one condition, participants explored a virtual environment through a head-mounted display (HMD), whereas in the control condition, participants explored the same environment through a standard monitor. Participants were all instructed to produce an interval of 4 minutes so that longer produced durations in an interval production task were evidence of underestimation. Adopting a prospective time estimation paradigm, the time intervals produced were compared between the two conditions. Results confirmed the time compression effect: participants in the VR condition reported longer produced intervals than participants in the control condition. Furthermore, the significant interaction with levels of prior experience with VR technologies suggests that time compression effects may be more pronounced for VR newcomers, thus favoring an interpretation in terms of familiarity. The present findings provide valuable insights into the perception of time in virtual environments, suggesting the importance of continued research in this emerging technology. Limits, implications, and the need for further research are finally discussed.

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Introduction

"Each individual has his measure of time that depends on where he is and how he is moving."
Stephen Hawking, A Brief History of Time

Virtual reality (VR) refers to immersive, computer-generated environments (Biocca, 1992) that can be experienced through one or more sensory channels (Burdea & Coiffet, 1994; Lee & Wong, 2014). VR technology allows individuals to interact with and explore virtual environments as if physically present (Slater, 2018).

Current and evolving technology allows for an immersive VR experience using head-mounted displays (HMDs). Recently, this technology has become very popular and has found a home in gaming (e.g., Meta Quest, HTC Vive), scientific research, and education.

Users of VR technologies often perceive time passing more quickly than veridical time when playing in virtual environments (Mullen & Davidenko, 2021). This phenomenon is called time compression: a longer actual duration is compressed into a shorter perceived experience (Mullen & Davidenko, 2021). Thus, in an interval production task, participants can produce longer intervals than the actual duration. In this regard, one study (Chirico et al., 2020) explored the efficacy of virtual reality versus music therapy in reducing elapsed time perception in patients receiving intravenous chemotherapy. It showed that the treatment with virtual reality results in a time compression effect, offering evidence for VR as a support tool in stressful conditions (Chirico et al., 2020). Evidence of time compression effects in VR has also emerged in cancer patients undergoing chemotherapy (Schneider et al., 2011). Aversive stimuli can produce time distortions by inducing negative arousal that interferes with cognitive mechanisms of time perception (Buhusi & Meck, 2005; Burle & Casini, 2001). Another study (Schatzschneider et al., 2016) investigated the interaction between the movement of a virtual sun and concurrent cognitive tasks on time estimation. According to the authors, the analysis of external *zeitgebers*, a German word used to describe events that calibrate an organism's biological clock, results in high working memory utilization. This also interferes with other tasks within the virtual environment result in increased cognitive load. However, the results of this study may have been biased by the experimental design. The authors adopted a within-subjects design: participants were exposed to the two experimental conditions (immersive vs non-immersive) in a fixed order. To overcome this limitation, a recent study (Mullen & Davidenko, 2021) investigated the effects of VR on time perception using a prospective temporal estimation paradigm. Participants were asked to play a maze-like game using both an HMD and a standard monitor. Similarly to what was proposed by Schatzschneider et al. (2016), the authors adopted a within-subjects design. However, they counterbalanced the order of presentation of the two experimental conditions (VR vs conventional monitor). In both conditions, participants were asked to stop the task when they believed 5 minutes had elapsed. Analyses revealed a significant interaction between trial presentation order and type of display (HMD vs. standard monitor), observing an underestimation effect in the first-trial data and an overestimation effect in the second-trial data. Nevertheless, a main effect of the experimental condition's presentation order was also found, with participants being more likely to overestimate time in whichever display (HMD vs. standard monitor) condition they started with. The authors also reported a strong correlation between the time intervals produced by participants for the two repeated tasks, suggesting that the time interval produced in the first block fostered an anchoring bias affecting time interval production in the second block (Mullen & Davidenko, 2021). More recently, another study (Unruh et al., 2023) adopting a within-subject approach showed that different levels of embodiment, that is the replacement of one's own body with a virtual one in VR (Maselli & Slater, 2013), had a significant effect on time perception, with participants reporting that time flowed more slowly when they were in the low embodiment condition compared to the medium and high embodiment conditions.

Although previous studies are in line with VR users' anecdotal accounts, they present a few limitations. Replicating the results, adopting different experimental procedures and designs, is thus needed to consolidate the conclusions. Moreover, we went a step further in the present study by studying the impact of familiarity with VR technologies as a possible individual difference that shapes time perception in VR environments.

One major factor of time perception is people's level of attention (Block & Zakay, 2001, Glicksohn, 2001; Tse et al., 2004; Zakay & Block, 1998). On the one hand, when engaged in a task or enjoying some activity, individuals pay less attention to the passage of time, and perceived duration becomes shortened. On the other hand, situations involving a heightened temporal awareness, such as boredom or waiting, lead to the perception of lengthening of external time (Brown, 1985). In this regard, the attention paid to the passage of time seems to be also influenced by familiarity with a particular event (Buhusi & Matthews, 2014). One recent study (Horstmann & Herwig, 2016) showed that low familiarity with a visual stimulus can capture and bind attention. In their work, Horstmann and Herwig (2016) adopted eye tracking technique to determine whether visual fixations could represent a proxy for attention. Results showed that when presented with different stimuli (novel vs. familiar colors), most of early visual fixations were directed at stimuli with which participants were less familiar with, suggesting greater attention toward novel stimuli compared to familiar stimuli (Horstmann & Herwig, 2016).

Cognitive models related to time perception and estimation (Zakay & Block, 1997) suggest that when no attention is paid to the passage of time, such as due to lack of available cognitive resources (Fiske & Taylor, 1991), pulses in the accumulator are not counted, leading to a time compression effect (Pouthas & Perbal, 2004; Pouthas & Pfeuty, 2010). Considering this evidence, we speculate that individuals characterized by unfamiliarity with VR environments would have allocated higher amounts of cognitive resources in exploring the immersive three-dimensional scene, compared with VR-experienced participants. Therefore, we speculated that prior levels of familiarity with VR could represent a significant moderating mechanism in the production of time intervals.

Time Compression as a Function of Familiarity With VR Technologies

The processing of temporal information plays a crucial role in several aspects of cognition (for a review, see Maniadakis & Trahanias, 2014). In this context, several descriptive-functional models have been proposed to represent how individuals cognitively perceive time. One of the earliest interpretations of the mechanisms underlying the perception of time duration is still one of the most influential (Gibbon, 1981; Woodrow, 1930). The model adopted an information processing perspective in which the pulses emitted by a pacemaker are temporally stored in an accumulator, the same way that a clock works (Gibbon, 1981; Grondin, 2010; Treisman, 1963). This approach inspired the subsequent pacemaker approach, which uses oscillations to represent clock ticks (Miall, 1989). At the beginning of a time interval, a switching device is activated and allows the pulses produced by the pacemaker to be transferred to the accumulator. At the end of the interval, the switch is deactivated, and the pulses collected in the accumulator form the representation of the duration, which is transferred to working memory and compared with reference values derived from previous experiences stored in the brain structures of long-term memory, to provide an evaluation (Matthews & Meck, 2016). Therefore, the perception of time duration is determined by the accumulation of temporal units within a specific timeframe.

Experimental paradigms that involve attention to the passage of time are known as prospective time estimation paradigms. That is, participants are aware that they need to estimate the duration of a time interval before it begins. When individuals pay more attention to time, it can result in the accumulation of a greater number of pulses over a specific duration (Zakay & Block, 1997). Indeed, to record an impulse and compare it with what is in memory, individuals must pay attention to time itself. Nevertheless, people have limited cognitive resources (Fiske & Taylor, 1991), which must be allocated between attention to temporal flow and other cognitive processes.

Considering this evidence, we speculated that individuals characterized by unfamiliarity with VR environments would have allocated more cognitive resources in exploring the immersive three-dimensional scene, compared with VR-experienced participants. Therefore, we speculated that the time compression effect in VR (e.g., Mullen & Davidenko, 2021; Schatzschneider et al., 2016) could be interpreted as a product of unfamiliarity with VR technologies. Considering a prospective time estimation task, we expected that users who were more familiar with VR would have more reference information in their working memory, which would help them estimate time intervals more accurately compared to users who are not as familiar with VR environments.

In addition to this, users unfamiliar with VR technologies should allocate more attention to the environment and less to time, in accordance with the results of studies on attention and new stimuli (Ernst et al., 2020; Hortsmann, 2002; Horstmann & Herwig, 2015). Therefore, familiarity with VR technologies could be a significant moderator of time perception in virtual environments. In other words, we hypothesized that users exploring an immersive virtual environment would report longer time interval durations than users exploring the same environment in a non-immersive mode (e.g., a standard monitor). However, such differences would emerge more strongly for participants unfamiliar with VR technologies, for whom exploring a virtual environment is something new, which requires more cognitive resources that, being limited (Fiske & Taylor, 1991), are taken away from the attention devoted to counting temporal pulses.

Study Overview

The first aim of the present work was to replicate previous findings about time perception in VR (e.g., Mullen & Davidenko, 2021; Schatzschneider et al., 2016) but switch from a within-subject to a between-subjects experimental design. The within-subject experimental design was indeed a limitation of previous research. Here, participants explored an immersive virtual environment through HMD in one condition. In the other condition, they explored the same three-dimensional environment through a conventional monitor. The second scope was to test whether familiarity with VR could influence time compression effects. For these reasons, the level of familiarity with virtual technologies was considered as a possible moderator in the relationship between the experimental condition and produced time durations.

Methods

Participants

The study was conducted after ethical approval was obtained from the local Department of Psychology's minimal risk research committee (protocol #RM-2021-486). All procedures carried out in the study were in accordance with the ethical guidelines of the APA and the ethical principles of the Declaration of Helsinki and the Oviedo Convention on Human Rights and Biomedicine. Full informed consent was obtained from participants before the start of the study. Participants were told that the study would take approximately 45 minutes. Because we did not want participants to understand the purpose of the study, a cover story was adopted. They were told that the study was investigating the individual's ability to pay attention to spatial navigation.

The sample is a convenience sample of undergraduate students (N = 159) in introductory psychology classes who voluntarily signed up to participate via the Sona System platform in exchange for course credits.

An a-priori power analysis was conducted with GPower (Faul et al., 2007) by considering the effect size (d = .693) reported by Mullen and Davidenko (2021) for an ANCOVA design (F-test) with 2 groups and one covariate. By fixing alpha and Power at the standard levels of .05 and .80 (Cohen, 2013), we estimated a priori the minimum sample size of N = 68.

We calculated a second a-priori sample size. Publication bias results in publishing papers reporting an overestimation of the true effect size. It has been suggested to adopt a safeguard power estimation to limit the impact of this effect (Perugini et al., 2014). Namely, we considered the lower boundary of the 80% confidence interval around the original effect size of Mullen and Davidenko (d = .51) to estimate a safer sample size. We kept fixed alpha and Power at the standard levels of .05 and .80 (Cohen, 2013), resulting in a minimum sample size of N = 123.

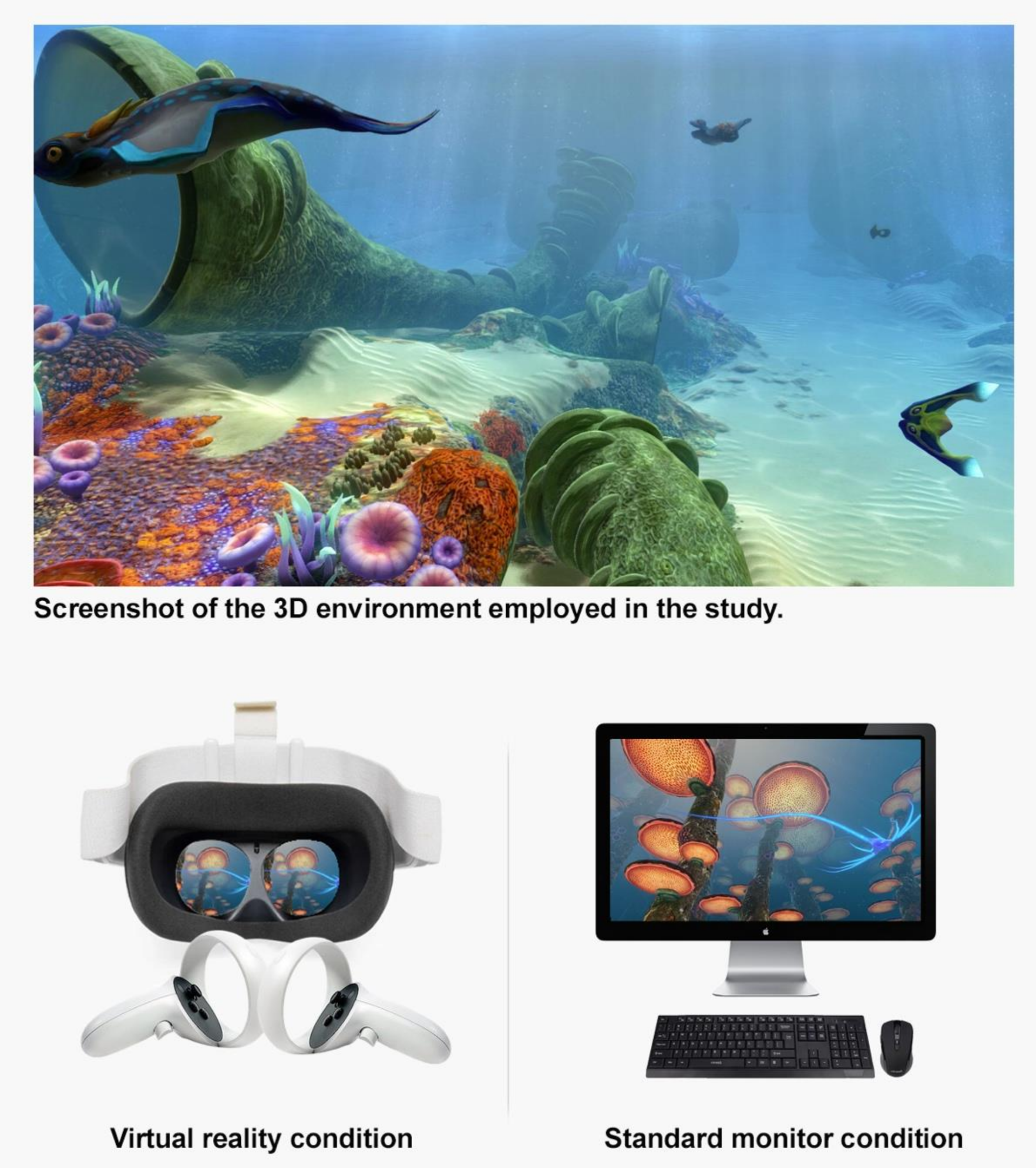
Data collection took place between October 2021 and May 2022. A total of 159 participants were recruited for the study. Of these, 5 were eliminated because they did not answer correctly to the manipulation check item (*Through what technology were you shown the three-dimensional environment?, virtual reality viewers/standard monitor*); In the preliminary instructions offered to the participants, they were asked to stop the exploration when they felt that four minutes had elapsed. Such a request could arouse suspicion as to the real purpose of the study (i.e., time estimation in VR environments) and influence participants' behavior. Therefore, participants were probed for suspicion at the end of the experimental session. Eighteen participants understood the aims of the study and were excluded from subsequent analyses; 3 were excluded because they reported problems related to sickness during the task, whereas 4 participants were not included because of technical issues with the experimental apparatus; 6 participants reported extremely short questionnaire response times (M = 75.5 seconds, SD = 42.13; overall sample mean values M = 2,552.39 seconds, SD = 1,920.26). Thus, the final sample consisted of 124 individuals (Min_{age} = 24, Max_{age} = 56, M_{age} = 27.46, SD = 3.74; 52.4% male, 46% female, 0.8% non-binary, 0.8% preferred not to answer) mainly from Italy (96%) but also from other nationalities (4%; Albania, Philippines, Moldova and Ukraine). In terms of education, 63.7% were post-graduate students, 35.5% reported to have obtained a bachelor's degree and 0.8% a master's degree.

Procedure and Measures

After obtaining participants' informed consent they were presented with socio-demographic measures. Therefore, before the experimental manipulation, participants were asked to report their level of familiarity with VR technologies by adopting three ad-hoc created items. Those items were: 1) *How would you rate your level of familiarity in using virtual reality technologies?* anchored with 1 = *no experience*, 2 = *beginner*, 3 = *competent*, 4 = *expert*, 5 = *very experienced*, 2) In the past, have you ever used stereoscopic viewers for virtual reality (e.g., Meta Quest)? anchored with 1 = *never*, 2 = *only once*, 3 = *a few times*, 4 = *several times*, 5 = *Very often* and 3) Have you ever used virtual reality applications in the past? anchored with 1 = *never*, 2 = *only once*, 3 = *a few times*, 4 = *several times*, 5 = *very often.*

The participants were then tested individually in the laboratory. They were randomly assigned to explore a 3D environment using either an HMD (Meta Oculus Rift; N = 65) or a standard 24-inch computer screen (N = 56). In addition, an unrealistic environment was chosen to avoid possible familiarity effects with the explored environment that could influence the results. Specifically, the adopted environment (i.e., Subnautica, Figure 1) is available for both VR and standard monitors. Moreover, this game is characterized by a high level of customization, which allowed us to hide any potential user interface confounding elements (e.g., weapons, tools, hands) so that participants could simply explore the environment. The adopted game is an open-world underwater alien environment, within which participants could explore a very large space without having to return to an already explored point. Special consideration was also given to the task by proposing an explorative rather than an interactive task (as in the study by Mullen & Davidenko, 2021) to avoid possible confounding arising from potential interaction difficulties.

Figure 1. *Screenshot of the Game Subnautica and the Experimental Setting Adopted in the Study*.



Note. The game was customized to allow participants only to explore the environment to the exclusion of any other type of interaction.

Participants were instructed to explore the three-dimensional environment freely. In the VR condition, participants navigated using two wireless hand controllers, while in the standard monitor condition, they used a keyboard and mouse.

Participants were then asked to stop the exploration when they felt four minutes had elapsed. It is important to note that this time interval was chosen because the expression "five minutes" is used in everyday speech to indicate any short time interval and, consequently, could have influenced the results. Before starting the experimental session, one research assistant verified that the participants were not wearing watches and were asked to leave their smartphones outside the testing room. The research assistant kept track of the time elapsed through a stopwatch, which was then recorded for each participant.

Next, control variables were assessed. The Presence Questionnaire (Witmer et al., 2005) was administered to measure participants' sense of presence. The original scale consisted of 29 items (see also the supplementary materials); a sample item was *How involved were you in the virtual environment experience?,* anchored with (1 = *not at all*, 7 = *very much*). Levels of cybersickness were assessed by adopting the Simulator Sickness Questionnaire (Kennedy et al., 1993), the most used measure of cybersickness symptoms in the context of 3D environments. The SSQ comprises 16 items (see also supplementary materials), corresponding to as many symptoms, such as nausea, stomach pain, dizziness, etc. Participants were asked to indicate how affected they felt by the presented symptoms immediately after the exploration task on a 4-point response scale (1 = *none*, 2 = *slight*, 3 = *moderate*, 4 = *strong*).

Finally, all participants were fully debriefed. The experimenter explained the use of deception and why it was necessary and disclosed the study's true purpose.

Results

Preliminary Analyses

Exploratory Factor Analysis (EFA) was performed to investigate the factor structure of the adopted measures. Analyses highlighted a one-factor structure for the familiarity scale. They also revealed that two items of the Presence Questionnaire and 1 item of the cybersickness scale loaded on multiple factors. Additionally, two items for the presence scale and two for the cybersickness scale presented loadings lower than 0.40. Accordingly, these items were not considered in subsequent analyses (see Additional Materials for full details).

After calculating the reliability for multi-item scales, Pearson's correlations were computed to assess the associations among the considered variables using SPSS software (v27). Correlations, along with means and standard deviations for each variable, are shown in Table 1 and Table 2.

Table 1. *Cronbach's Alpha, Means, and Standard Deviations.*

	α	*M*	*SD*
1. Age	-	27.46	3.747
2. Education	-	3.37	0.502
3. Familiarity with VR	.700	1.857	0.667
4. Sickness	.863	0.385	0.427
5. Presence	.868	4.444	0.689
6. Produced durations	-	1.450	0.500

Table 2. *Pearson Correlations.*

	1	2	3	4	5	6
1. Age	1					
2. Education	$.428^{***}$	1				
3. Familiarity with VR	.172	.054	1			
4. Sickness	−.026	.106	$-.184^{*}$	1		
5. Presence	.000	−.142	−.073	−.053	1	
6. Produced durations	−.017	.045	$-.267^{**}$	.015	.013	1

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$, $N = 124$.

To test whether the experimental condition (coded as 1 = *virtual reality* and 2 = *standard monitor*) was associated with the variables of interest, independent-samples *t*-tests were conducted. In line with previous studies (see Kolasinski & Gilson, 1998), a significant association between the experimental condition and levels of cybersickness was found: participants in the VR condition reported overall higher sickness ($M = 0.53$, $SD = 0.48$) than participants in the standard monitor condition; $M = 0.21$, $SD = 0.26$, $t(122) = 4.45$, $p < .001$. No significant differences emerged for the presence index $t(122) = 1.08$, $p = .280$ nor for familiarity with VR technologies $t(122) = 0.726$, $p = .146$. Consequently, all subsequent analyses entered the sickness index as a control variable.

Therefore, an ANCOVA was performed to test for possible differences in time interval production across the two conditions, considering the experimental condition as the factorial predictor, time interval durations as the dependent variable, and the sickness index as a covariate variable. Results showed a significant effect of the experimental condition on time durations, $F(2,121) = 4.09$, $p = .045$, $\eta_p^2 = .033$. In other words, participants in the

VR condition produced longer interval durations (*M* = 354.41 seconds, *SD* = 196.66) than participants in the control condition (*M* = 298.21, *SD* = 99.10). No significant effects of sickness were found (*p* = .550).

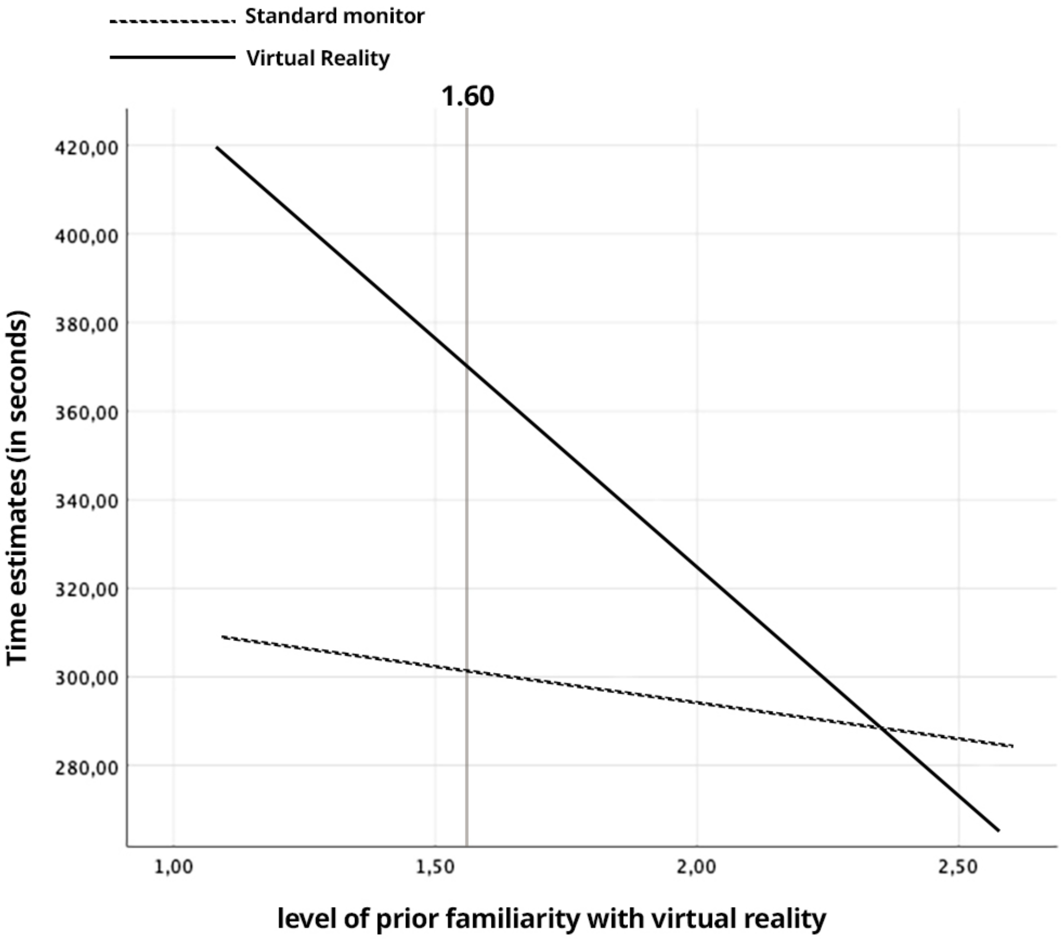
Conditional Process Model

Given the significant negative correlation between the level of prior familiarity with virtual reality and durations (*r* = −.267, *p* = .003), to further investigate the role of familiarity with VR technologies, a moderation analysis was conducted using the PROCESS macro (v4.1; Hayes, 2017). The predictor variable was the experimental condition, the moderator was the index of previous experience with VR technologies, and the outcome variable was the interval duration. The sickness index was considered as a control variable.

The interaction between the moderating variable (i.e., VR familiarity) and the experimental condition was probed using the Johnson & Neyman (1936) technique (see also Bauer & Curran, 2005; Hayes & Matthes, 2009), which avoids the need to define arbitrarily values of familiarity (e.g., “low”, “moderate” and “high”). Instead, it identifies the regions of a continuum where the effect of previous experience with VR technologies on time estimation is statistically significant and where it is not.

Regression analysis highlighted the main effect of the experimental condition *t*(119) = −2.32, *p* = .021, *b* = −203.67, and the main effect of familiarity *t*(119) = −2.71, *p* = .007, *b* = −189.08 on produced durations. No significant results were found for cybersickness (*p* = .417). However, these main effects were qualified by the predicted interaction between the experimental condition and familiarity with VR technologies, *t*(119) = 1.96, *p* = .050, *b* = 86.14. As seen in Figure 1, for levels of familiarity lower than 1.60 (31.45 percentile), participants who explored the 3D environment using a head−mounted display seem to report more significant temporal distortion than participants in the standard monitor condition. There was a significant negative relationship between produced time durations and familiarity with VR technologies for participants in the VR condition, *t*(119) = −3.29, *p* = .001, *r* = −.31, but not for participants in the standard monitor condition, *t*(119) = −0.54, *p* = .586, *r* = −.103.

Figure 2. *Relationship Between Produced Durations and Prior Familiarity With VR Technologies for Participants in the VR and the Standard Monitor Conditions.*



Note. For familiarity scores lower than 1.60, participants who explored the 3D environment with a VR headset underestimated the time spent on the task.

Discussion

The first aim of the present study was to replicate the time compression effect reported by Mullen and Davidenko (2021) in immersive VR environments. This aim was successfully achieved: we found a significant effect of the experimental condition (VR vs standard monitor) on production of time interval durations. Participants in the VR condition had a more prominent time compression than participants in the control condition. However, compared to and building on their work, the present study also allows us to deepen the conditions within which the time compression effect occurs, that is, when the experience of a virtual environment is something new. In this regard, previous literature in cognitive psychology suggests that time perception is related to attention (Zakay & Block, 1997; 1998) and familiarity with perceived stimuli (Ernst et al., 2020; Hortsmann, 2002; Horstmann & Herwig, 2016). Therefore, it could be that participants in the VR condition allocated more attention to the three-dimensional environment because of the experience of newness. This would have led to a later indication of the end of the 4 minutes required in the task, shifting attention away from the passage of time and leading to fewer pulses in the accumulator.

Our findings can also be interpreted under the light of the Flow Theory (Csikszentmihalyi, 1990). The Flow State describes a mental condition by which people feel deeply focused and involved when performing a particular activity. When in this state, people report feeling completely absorbed with what they are doing, a greater sense of control over the outcome of the activity, and greater self-awareness (Csikszentmihalyi, 1988). Previous research has shown that flow state is associated with an altered perception of time (see Hancock et al., 2019 for a meta-analysis) even when performing activities in a virtual environment (Rutrecht et al., 2021). Thus, it is possible that participants in our study experienced a flow state resulting in distorted time perception. The role of the flow state should, therefore, be considered in subsequent studies.

Another interpretation is offered by the Dynamic Occupation in Time theoretical model (DOiT; Larson, 2004; Larson & von Eye, 2006). The DOiT model posits that while performing a given task, individuals can engage in either an automated or creative mode (Larson & Von Eye, 2010), depending on their proficiency in executing the activity (Larson, 2004; Larson & von Eye, 2006). Levels of involvement in the activity can foster a deeper attentional focus and more engagement in the activity. The deeper the engagement in the activity and the greater the demand for skills and cognitive resources, the greater the perception of the speed of time (Larson & Von Eye, 2010). In this regard, recent research has shown that VR contents—compared to flat 2D contents—produce greater cognitive load (Redlinger & Shao, 2021). In accordance with cognitive models of temporal perception, a higher cognitive load resulting from the virtual experience might have thus diminished the resources allocated to counting the impulses in the accumulator, leading to a time compression effect (see also Pouthas & Perbal, 2004; Pouthas & Pfeuty, 2010). Future studies could thus consider levels of cognitive load as a potential psychological mechanism underlying the effects of temporal compression when experiencing virtual environments.

Another possibility is that participants may have produced longer intervals simply because they were enjoying the task and were not interested in stopping. Indeed, since they did not know the aim of the study, they may have ignored the request to stop when they believed that 4 minutes had elapsed. Future studies should take this aspect into account.

Previous evidence has also shown that images in VR elicit greater arousal than the same images displayed on a conventional monitor (Estupiñán et al., 2014; Tian et al., 2021). Therefore, our findings may have been driven by physiological activation. Nevertheless, the attentional gate model (Zakay & Block, 1998) postulates that greater arousal should be associated with time dilation rather than compression effects. Given that, participants in the VR condition produced longer time interval than participants in the control condition. It is thus reasonable to exclude that arousal influenced our results. Future studies should explore this aspect in more detail by measuring physiological parameters (e.g., skin conductance, heart rate) as markers of arousal levels.

Considering the pacemaker-accumulator theoretical framework, impulse generation depends on natural body rhythms (Meissner & Wittmann, 2011; Pollatos et al., 2014; Wittmann, 2009). Nevertheless, the visibility of one's own body is reduced when experiencing virtual environments because users wear head-mounted displays (Pastel et al., 2020). Related to this evidence, recent studies suggested that body awareness (Droit-Volet et al., 2020) and embodiment processes (Unruh et al., 2023) play a critical role when considering time perception in virtual environments. Therefore, one potential explanation for our findings might be found in the differences in interoceptive and body awareness, as well as in body visibility, between the experimental conditions (VR versus standard monitor).

The second goal of the present study was to test the conditional processes involved in the relationship between the exploration of a VR environment and time perception. Our results offer preliminary evidence that time compression effects could be a function of prior familiarity with VR, with longer time durations produced by participants who reported to be newcomers to VR technologies.

This work is not free from limitations that we need to point out. The first limitation consisted of testing mainly psychology students. Future studies should consider a more diverse sample to ensure greater variability favoring more generalizable results.

Second, we did not vary the target value of the time intervals to be produced by the participants (i.e., 4 minutes). Future studies may focus on varying the target duration or adopting a retrospective time estimation approach. Notably, some studies (Bisson & Grondin, 2013; Tobin et al., 2010) have shown that time compression effects occur when interacting with digital technologies for more than 30 minutes. Therefore, future research should also consider estimating longer intervals (e.g., 30 minutes or more).

Further studies should also focus on the role of emotions. The mood facilitation hypothesis (Bar-Haim et al., 2010; Droit-Volet, 2013; Tipples, 2008) suggests that an individual's internal emotional state can influence time perception. Negative emotions can lead to longer perceived durations of temporal intervals (Angrilli et al., 1997; Droit-Volet & Meck, 2007; Droit-Volet et al., 2004).

It is worth noting that Mullen and Davidenko (2021) used an interactive task for their manipulation (i.e., a maze-like game). Instead, we chose to use a simpler exploratory task to make the experience easily accessible to newcomers. Future studies may, therefore, test the role of familiarity by considering more complex tasks as well. A longitudinal design involving participants unfamiliar with VR is also encouraged. We predict that if differences in produced intervals are dependent on familiarity, time compression effects could emerge in the first wave of data collection and diminish significantly in subsequent sessions as participants gain experience with VR over multiple experimental sessions.

Conclusion

According to many philosophers, we do not perceive reality as it is, but knowledge of it arises from two absolute and independent dimensions: space and time (Van Cleve, 2003). However, our results seem to indicate that the perception of time may depend on the space in which people experience reality: participants in our study estimated time differently depending on how they explored a three-dimensional environment (immersive VR vs non-immersive display).

Mullen and Davidenko (2021) reported that time compression effects could be beneficial when confronted with unpleasant but necessary situations, such as prolonged medical treatments or long-distance travel. However, it is crucial to understand the specific conditions under which time compression effects occur in VR environments. Our results provide preliminary evidence that these effects could be beneficial, especially for individuals with low familiarity with VR. Therefore, deepening the relationship between time perception and individual differences is an important goal for the following studies in the field.

To conclude, it is essential to better understand the unexplored psychological dimensions that govern the perception of time in VR environments to design appropriate immersive experiences. We believe that what Stephen Hawking said about the perception of time can also be applied to the emerging metaverse (Mystakidis, 2022), understood as a digital world in which users can experience new places and new forms of social interaction with their own "personal measure of time".

Conflict of Interest

The authors have no conflicts of interest to declare.

Authors' Contribution

Anna Manfredi: conceptualization, data curation, writing—original draft. **Sofia Dal Lago:** data curation, writing—review & editing. **Daniele Romano:** conceptualization, methodology, writing—review & editing. **Alessandro Gabbiadini:** conceptualization, methodology, formal analysis, writing—original draft, supervision.

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Appendix

Exploratory Factor Analyses

Familiarity With VR Technologies

Three items were created for assessing previous familiarity with VR technologies. The items were 1) *How would you rate your level of familiarity in using virtual reality technologies?* anchored with 1 = *no experience*, 2 = *beginner*, 3 = *competent*, 4 = *expert*, 5 = *very experienced*, 2) *In the past, have you ever used stereoscopic viewers for virtual reality (e.g., Meta Quest)?* anchored with 1 = *never*, 2 = *only once*, 3 = *a few times*, 4 = *several times*, 5 = *Very often* and 3) *Have you ever used virtual reality applications in the past?* anchored with 1 = *never*, 2 = *only once*, 3 = *a few times*, 4 = *several times*, 5 = *Very often.*

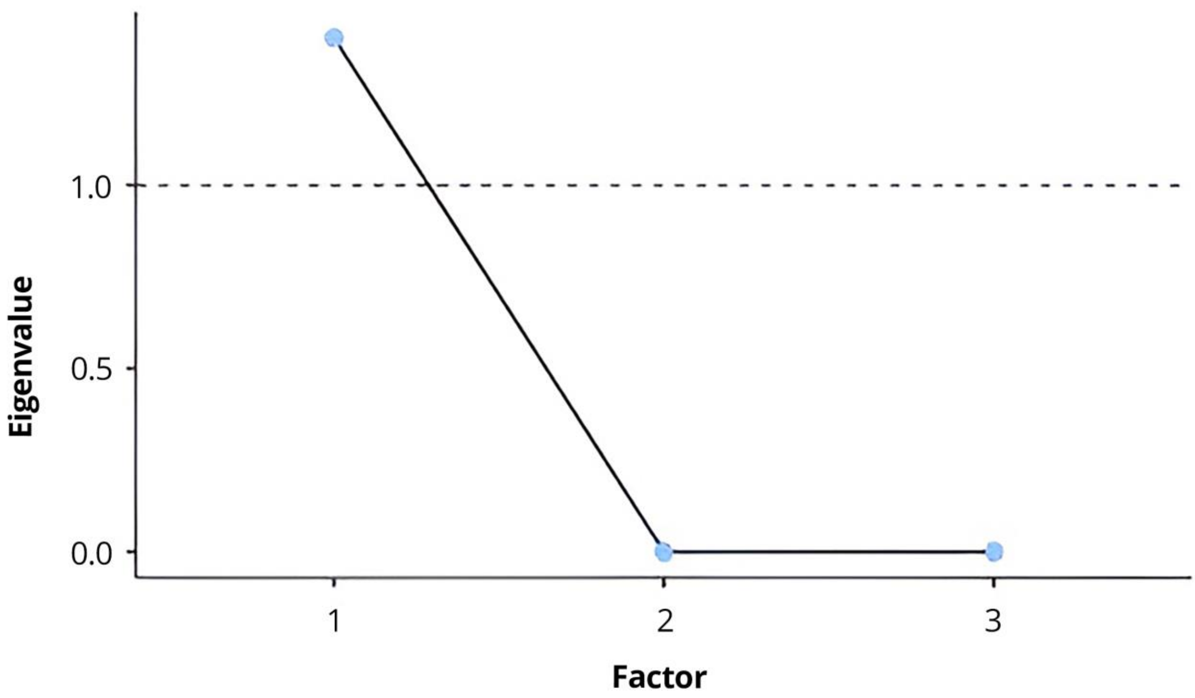
Exploratory factor analysis (see Table A1 and Figure A1) conducted with the maximum likelihood method, Oblimin rotation and based on eigenvalues greater than 1.0 indicates a single-factor structure, explaining 46.7% of the variance. Kaiser-Meyer-Olkin values for individual items were greater that .665, all above the acceptable limit of .5 (Field, 2009). Bartlett's test of sphericity, $\chi^2(3) = 72.5$, $p < .001$, indicated that correlations between items were sufficiently large for EFA. Items loadings are reported in Table A1.

Table A1. *Item Loadings for the Familiarity Measure.*

	Factors			Uniqueness
	1	2	3	
PQ_4	0.722			.481
PQ_18	0.647			.462
PQ_3	0.601			.414

Note. Maximum likelihood extraction with oblimin rotation.

Figure A1. *Scree Plot Showing Eigenvalues From EFA for the Familiarity Ad-Hoc Created Measure.*



Presence Questionnaire Scale

The original formulation of the Presence Questionnaire Scale (Witmer et al., 2005), suggests a four-factor structure: Involvement, Sensory fidelity, Adaption/immersion, and Interface quality.

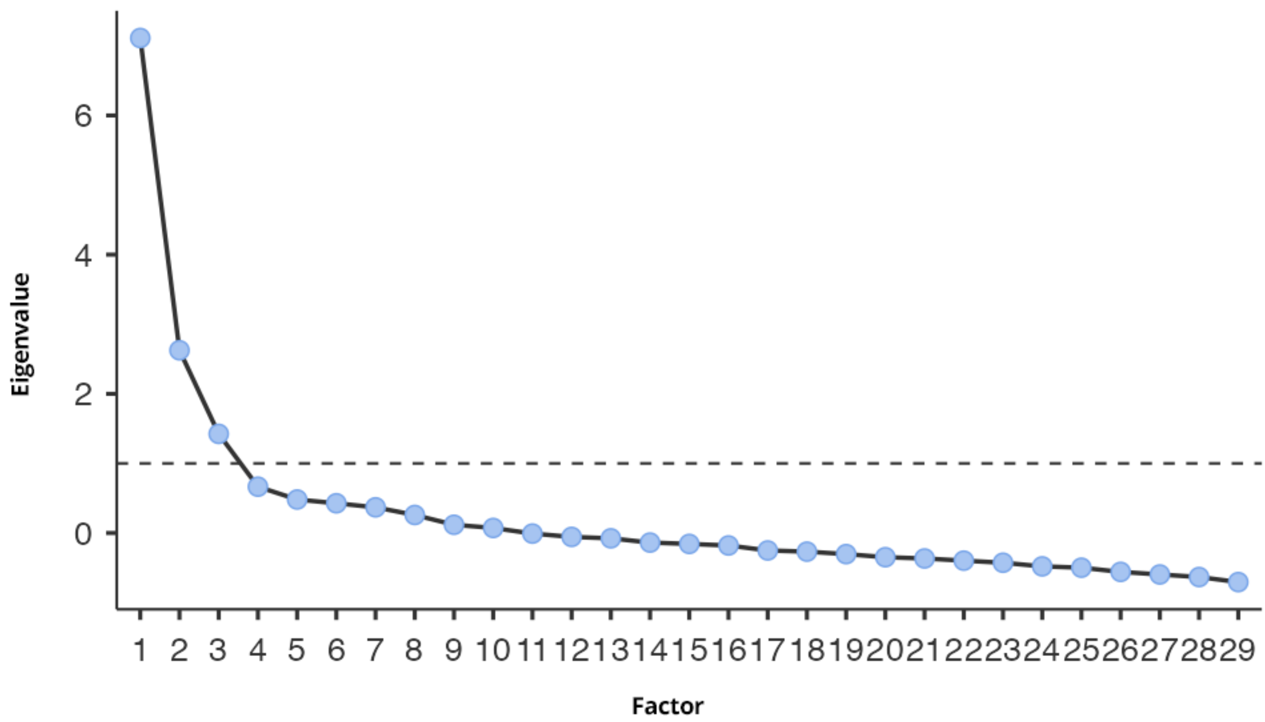
Exploratory factor analysis (see Table A2 and Figure A2) conducted with the maximum likelihood method, Oblimin rotation and based on eigenvalues greater than 1.0 indicates a three-factor structure, explaining 40.9% of the variance. Kaiser-Meyer-Olkin values for individual items were greater that .585, all above the acceptable limit of .5 (Field, 2009). Bartlett's test of sphericity, $\chi^2(406) = 1{,}616$, $p < .001$, indicated that correlations between items were sufficiently large for EFA. Items loadings are reported in Table A2. Items 8, 9 and 25 showed loadings lower than 0.40. Therefore, they were not considered for the calculation of the aggregate index.

Table A2. *Item Loadings for the Presence Questionnaire Scale.*

	Factors			Uniqueness
	1	2	3	
PQ_4	0.722			.481
PQ_18	0.647			.462
PQ_3	0.601			.414
PQ_10	0.596			.605
PQ_27	0.589			.611
PQ_15	0.589			.647
PQ_14	0.576			.625
PQ_21	0.574			.657
PQ_28	0.554			.683
PQ_16	0.551			.692
PQ_7	0.545			.602
PQ_20	0.540			.752
PQ_6	0.510			.646
PQ_29	0.463			.500
PQ_24	0.443			.822
PQ_8				.743
PQ_25				.530
PQ_17		0.786		.392
PQ_13		0.772		.394
PQ_2		0.605		.548
PQ_1		0.590		.617
PQ_26		0.571		.606
PQ_23		0.451		.770
PQ_19		0.438		.814
PQ_22		0.436		.795
PQ_9				.868
PQ_11			0.930	.153
PQ_12			0.793	.380
PQ_5			0.775	.330

Note. Maximum likelihood extraction with oblimin rotation. Item loadings < 0.40 are not reported.

Figure A2. *Scree Plot Showing Eigenvalues From EFA for the Presence Measure*.



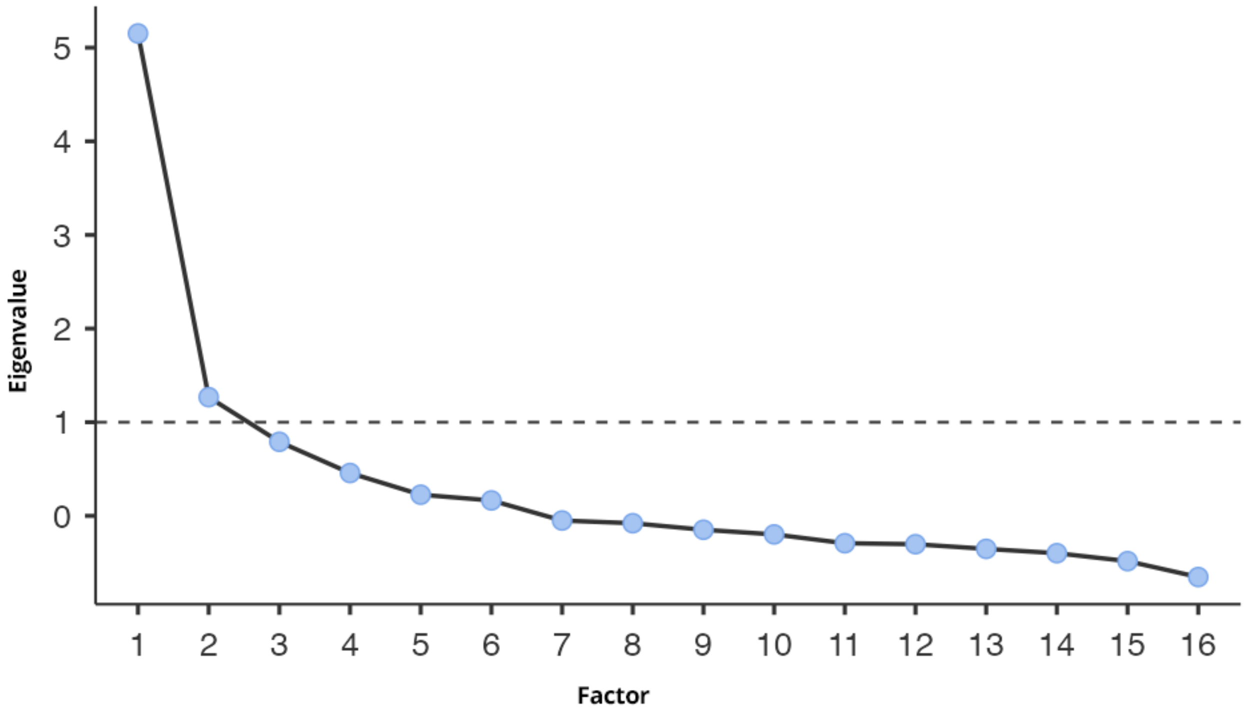
Simulator Sickness Questionnaire

The original formulation of the Simulator Sickness Questionnaire (Kennedy et al., 1993) presents a three-factor structure: Nausea, Oculomotor and Disorientation. Exploratory factor analysis (see Table A3 and Figure A3) conducted with the maximum likelihood method, Oblimin rotation and based on eigenvalues greater than 1.0 indicates a three-factor structure, explaining 41.3% of the variance. Kaiser-Meyer-Olkin values for individual items were greater that .611, all above the acceptable limit of .5 (Field, 2009). Bartlett's test of sphericity, $\chi^2(120) = 1{,}008$, $p < .001$, indicated that correlations between items were sufficiently large for EFA. Items loadings are reported in Table A3. Items 6, 11, 13 and 16 showed loadings lower than 0.40. Therefore, they were not considered for the calculation of the aggregate index.

Table A3. *Item Loadings for the Simulator Sickness Scale.*

	Factors		Uniqueness
	1	2	
SSQ_10	0.786		.462
SSQ_2	0.730		.368
SSQ_3	0.705		.464
SSQ_4	0.682		.519
SSQ_9	0.573		.737
SSQ_12	0.497		.507
SSQ_5	0.424		.760
SSQ_11			.829
SSQ_13			.646
SSQ_15		0.907	.263
SSQ_8		0.898	.174
SSQ_1		0.727	.258
SSQ_14		0.475	.745
SSQ_7		0.412	.814
SSQ_16			.927
SSQ_6			.918

Figure A3. *Scree Plot Showing Eigenvalues From EFA for the Simulator Sickness Questionnaire*.



Cognitive Absorption

On an exploratory basis a measure of cognitive absorption was also included, which was hypothesised as a possible mediating mechanism of the relationship between the experimental condition (virtual reality vs. standard monitor) and the prospective estimation of time intervals. Cognitive absorption is defined as a state of deep involvement with a specific activity, leading individuals to such an intense concentration that they ignore everything else (Magni et al., 2013). The original formulation of this measure (Agarwal & Karahanna, 2000) assumes five different dimensions: temporal dissociation, focused immersion, enjoyment, control, and curiosity. Overall, these five dimensions capture individual's experience with new software. In this regard, adopting the theoretical framework of the Technology Acceptance Model (TAM; Davis et al., 1989), Agarwal and Karahanna (2000) found that cognitive absorption influences technology intention and usage behaviour, acting as a proximal antecedent of perceived ease of use and perceived usefulness. The scale was originally validated with reference to the use of the World Wide Web and consists of 20 items. However, due to a clerical error, the version used in the present study consisted of 19 items.

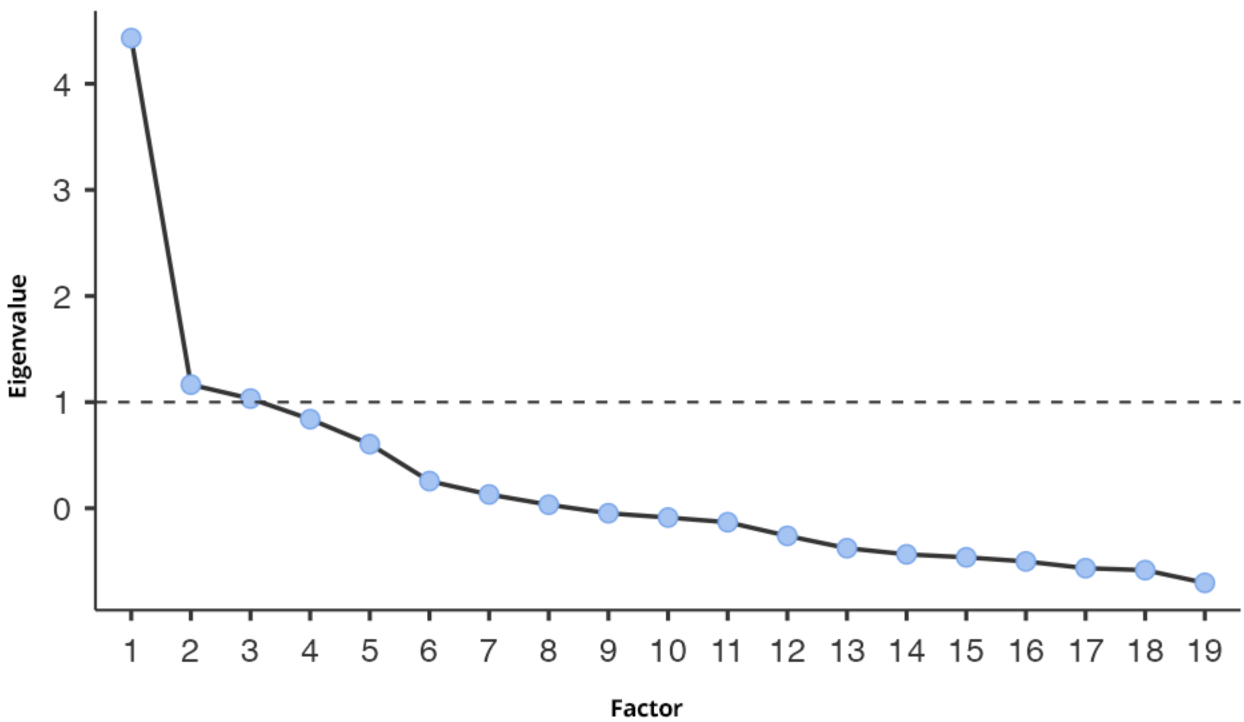
Exploratory factor analysis (see Table A4 and Figure A4) conducted with the maximum likelihood method, Oblimin rotation and based on eigenvalues greater than 1.0 indicates a three-factor structure, explaining 37.9% of the variance. Some of the Kaiser-Meyer-Olkin values for individual items were below the acceptable threshold of .5 (Field, 2009). Bartlett's test of sphericity, $\chi^2(171) = 961$, $p < .001$, indicated that correlations between items were sufficiently large for EFA. Items loadings are reported in Table A4. Items 1, 2, 3, 4, 5, 8, 9 and 16 showed loadings lower than 0.40. Therefore, they were not considered for the calculation of the aggregate index. Consequently, due to the measurement problems just described, we decided not to consider this measure in the study.

Table A4. *Item Loadings for the Cognitive Absorption Scale.*

	Factors			
	1	2	3	Uniqueness
Cognitive_Absorption_10_enjoyment	0.929			.200
Cognitive_Absorption_11_enjoyment	0.899			.206
Cognitive_absorption_13_enjoyment_R	0.585			.541
Cognitive_Absorption_19_curiosity	0.511			.498
Cognitive_Absorption_12_enjoyment	0.507			.609
Cognitive_Absorption_6_immersion	0.403			.575
Cognitive_Absorption_4_time				.904
Cognitive_Absorption_3_time				.967
Cognitive_Absorption_8_immersion_R				.976
Cognitive_Absorption_2_time				.982
Cognitive_Absorption_18_curiosity		1.016		.005
Cognitive_Absorption_17_curiosity		0.822		.268
Cognitive_Absorption_1_time				.981
Cognitive_Absorption_14_control			0.844	.300
Cognitive_absorption_15_control_R			0.777	.407
Cognitive_Absorption_7_immersion			0.446	.631
Cognitive_Absorption_16_control				.811
Cognitive_Absorption_5_immersion				.959
Cognitive_Absorption_9_immersion				.986

Note. Maximum likelihood extraction with oblimin rotation. Item loadings < 0.40 are not reported.

Figure A4. *Scree Plot Showing Eigenvalues From EFA for the Cognitive Absorption Measure.*



We also tested a mediation model by considering the index of cognitive absorption as the mediators, the experimental condition as the focal predictor and the time estimates as the outcome variable. The cognitive absorption index was computed by considering items with loadings above 0.40. The software used was SPSS v27 with the PROCESS macro (Hayes, 2017; v4.0). The cybersickness index was considered as a covariate in the tested model. Results showed that the cognitive absorption index did not significantly mediate the relationship between the experimental condition and time estimates, IE = 2.87, 95% CI [−2.90, 14.14].

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