How Self-Motion in Virtual Reality Affects the Subjective Perception of Time

Stefan Weber[1, 2, *], David Weibel[1], and Fred W. Mast[1]

[1]Institute of Psychology, University of Bern, Bern, Switzerland

[2]Swiss Distance Learning University, Brig, Switzerland

Author Note

* Corresponding author. Institute of Psychology, University of Bern, Fabrikstrasse 8, 3012 Bern, Switzerland. E-mail address: stefan.weber@psy.unibe.ch

Abstract

The velocity of moving stimuli has been linked to their experienced duration. This effect was extended to instances of self-motion, where one's own movement affects the subjective length of time. However, the experimental evidence of this extension is scarce and the effect of self-motion has not been investigated using a reproduction paradigm. Therefore, we designed a virtual reality scenario that controls for attention and eliminates the confounding of velocity and acceleration. The scenario consisted of a virtual road on which participants (n = 26) moved along in a car for six different durations and with six different velocities. We measured the subjective duration of the movement with reproduction and direct numerical estimation. We also assessed levels of presence in the virtual world. Our results show that faster velocity was connected to longer subjective time for both forms of measurement. However, the effect showed deviations from linearity. Presence was not associated with subjective time and did not improve performance in the task. We interpreted the effect of velocity as corroborating previous work using stimulus motion, which showed the same positive association between velocity of movement and subjective time. The absence of an effect of presence was explained in terms of a lacking dependency of time on characteristics of the virtual environment. We suggest applying our findings to the design of virtual experiences intended for inducing time loss.

Keywords: time perception, self-motion, presence, virtual reality

1. Introduction

The dominant view in time perception research presumes the existence of an internal clock (cf. Grondin, 2010). A prominent example is the pacemaker-counter model, according to which subjective time is influenced by some form of pacemaker that tracks time by generating impulses in regular intervals (Gibbon, 1977; Gibbon et al., 1984; Rammsayer & Ulrich, 2001; Treisman, 1963). The state-dependent-network is yet another model which has received support in the domains of motor control and visual perception (Eagleman, 2008; Grondin, 2010; Karmarkar & Buonomano, 2007). According to this model, time perception is an intrinsic process that is based on time-dependent changes in the state of neural activity. There is experimental support for either model of time perception (cf. Grondin, 2010; Ivry & Schlerf, 2008).

Irrespective of the mechanism, our subjective time apparently is not only depending on temporal information but also on unrelated sensory input: for example, the overall magnitude of stimuli such as size, luminosity, or motion velocity has been shown to affect the subjective estimation of presentation time (Matthews et al., 2011; Rammsayer & Verner, 2014; Xuan et al., 2007). Brown (1995) reported a linear relationship between the velocity of moving stimuli and the subjective length of the duration of their appearance. Higher velocities led to longer subjective estimates of presentation times, independent of the actual presentation time, which varied from 6 to 18 s. This positive association between stimulus motion velocity and perceived duration was subsequently reproduced in several other studies (Gorea, & Kim, 2015; Kaneko, & Murakami, 2009; Tomassini et al., 2011). Based on similar findings, Walsh (2003, 2015) proposed the ATOM model (A Theory Of Magnitude). The ATOM model postulates a general mechanism for detecting magnitudes across sensory modalities. Specifically, the model assumes strong intercorrelations between space, time, and numerosity judgments.

Surprisingly, only few studies looked at an effect of velocity of one's *own body motion* on the subjective experience of time. In this study, we suggest a new way to study this effect of self-motion. We used immersive VR technology to achieve high control over stimulus variables while maintaining external validity. We aimed to explore whether velocity of self-motion affects the judgment of time in a prospective time judgment task. Self-motion was induced by vection in a car-driving task. Participants wore a head-mounted display (HMD) and moved along a virtual road leading through a city environment as co-drivers in a car. The velocity of the movement as well as its duration were systematically varied. Participants had to express the subjective duration of their movement explicitly by numerical estimation and implicitly by reproduction of the target duration. Subjective time in immersive virtual environments (IVEs) has applied potential in activities where timing is important.

1.1 Motion and Perception of Time

If motion is actively generated by participants, it is no longer possible to differentiate between the effect of self-motion and the motor efforts that require attentional resources. According to internal clock models, tasks with higher attentional demand lead to shorter subjective time because there are fewer resources available to keep track of timing pulses (cf. Brown, 2008). Studies that engaged participants in stationary physical exercise (either on a treadmill or on an ergometer) found an underestimation of time compared to control conditions without exercise (Kroger-Costa et al., 2013; Vercruyssen et al., 1989). However, in these studies the (active) self-motion is confounded with the exercise: Similar to a dual-task paradigm, attentional resources are captured by the exercising task and are thus not fully available for the timing task. It is our goal to overcome this limitation and to ensure that the above-mentioned results are indeed the result of self-motion. Therefore, participants in our study experienced *passive* self-motion.

Only few studies used passive self-motion to investigate the effect of motion velocity on time perception. Participants were moved on rotating devices in the dark and had to produce time intervals by regularly tapping a button while being moved (Binetti et al., 2010; Capelli et al., 2007). Tapping rate was higher in accelerated motion trials. These studies indicated that with increasing acceleration the subjective time estimation seems to shorten (i.e. there is an underestimation of time in fast acceleration). This seems to contradict the effects of visually induced motion via stimuli, where increased motion velocity led to an overestimation of time. It is possible that faster passive acceleration required more attentional resources than slower acceleration or no motion (Capelli et al., 2007). Ramped up movements could be more demanding for participants and require more attention to sensory input during self-motion. Therefore, it is possible that ramped up movements capture attentional resources and, thus, lead to shorter produced time intervals. In these experiments, participants were blindfolded, which means that any effect of motion can only be attributed to vestibular perception. Additionally, the vestibular system can only detect changes in velocity, and this limits the possibilities of investigating self-motion at constant velocity. Furthermore, the mean velocity of motion was confounded with the length of the acceleration and deceleration phase. While there is certainly an interest in studying real passive movement, the duration needed for accelerating or decelerating cannot be discerned from the effect of constant velocity when only short real passive displacements are applied.

In Brehmer's study (1970), participants were co-drivers in a car on the highway. While looking forward through the front window, they had to produce intervals that were multiples of the length of previously introduced time intervals (*magnitude production* paradigm). For example, if they were introduced to a 10 s interval before entering the car and then, while moving on the highway, the experimenter asked for an interval of twice the length of the standard interval, they had to produce a 20 s interval. When the car was going faster (i.e. driving 100 kph instead of 50 kph), they produced longer intervals. Although attention was effectively held constant and trials were long enough to limit the influence of acceleration and deceleration phases, there are still problems associated with the magnitude production paradigm. It has been argued that humans are not capable of making accurate quantitative judgments on a ratio scale, as it is necessary in magnitude production (cf. Narens, 1996). Investigations by Ellermeier and Faulhammer (2000) and Zimmer (2005) showed that this objection was corroborated and they concluded that participants are unable to produce accurate quantities.

Van Rijn (2014) showed participants a video of a virtual car moving on a road. The video was either sped up or slowed down to create trials with differing motion velocity. The reference velocity was 100 kph and there were additional trials with 50, 75, 125, and 150 kph. A *magnitude comparison* paradigm was chosen for judging time. Participants were first introduced to a standard duration and, later, had to compare each trial to this standard duration. The intended differences between the standard duration and the trial durations were in the range of -0.2 to +0.2 seconds. The result was that an overestimation of time was present in the higher velocity conditions, whereas an underestimation could be observed in lower velocities. This positive effect of velocity resembles the effect of stimulus motion on subjective time. The study had a high validity and effectively controlled for effects of attention and acceleration. One limitation of the experiment is, however, that only time differences within the subsecond range were presented. Interestingly, Brown (1995) also found an overestimation for faster motion and for moving stimuli. In this case, however, vection induced from the moving surroundings of the car was responsible for the effect.

Taken together, there were mixed results about the effect of self-motion velocity on time perception. Some studies contradict the results of stimulus motion and found that fast passive self-motion led to an underestimation of time, while others support the results of stimulus motion and found an overestimation. This discrepancy can be explained with differences in study design: If attention was held constant, faster motion led to an overestimation of time (Brehmer, 1970; van Rijn, 2014). We propose that self-motion after controlling for attention will produce similar results as those found in studies using visual stimulus motion: faster motion leads to longer subjective time judgments. Furthermore, we propose that this relationship is linear. Therefore, we state the following two hypotheses:

Hypothesis 1: Higher target velocities are associated with longer subjective durations and lower target velocities are associated with shorter subjective durations.

Hypothesis 2: The effect of target velocity on subjective duration is linear.

An important limitation of previous research about the effect of self-motion on subjective time is that time perception was measured using different paradigms. None of these paradigms involved an explicit measure of time experience. Additionally, there was no study that applied a reproduction paradigm. Reproduction is one of the standard paradigms in time perception research (Grondin, 2010). Reproduction methods show less inter-subject variability and are less dependent on socially learned time units than other forms of measurements such as production of time and verbal reports, according to Rammsayer and Verner (2014). The same authors argue that time reproduction is the preferred method to investigate effects on prospective time perception since it represents a ‘natural’ form of measurement. Accordingly, we will include reproduction measures in our study.

A second addition of our study is the use of immersive VR technology. We propose that a VR paradigm will help to isolate the effect of self-motion velocity on time perception and enhance external validity: VR allows to control for effects of attention since neither motor effort nor ramp-up phases are required. Furthermore, it allows stricter control over the surroundings than real world scenarios (Loomis et al., 1999). At the same time, it imitates real life situations and provides high external validity. IVEs possess a range of additional depth cues and more realistic motion than 2D environments (Armbrüster et al., 2008).

Taken together, our study combines and extends the experiments by Brehmer (1970) and van Rijn (2014). It connects realistic car motion from a first person point of view with the possibilities of generating true constant velocity trials. We are the first to use a VR paradigm for assessing the effect of self-motion on subjective time. We are also the first to use reproduction for assessing subjective time in the context of self-motion. Finally, another addition of our experiment is the assessment of presence as described in the next section.

1.2 Presence and Perception of Time

Presence is the degree to which one feels immersed, or present, in a virtual world. It is often defined in the literature as the feeling of being physically present in a technically mediated environment (Steuer, 1992; Weibel et al., 2011; Wissmath et al., 2010). Presence has already been linked to time perception in games. Empirical studies found that a high level of presence was related to greater time loss (Hägni et al., 2007; Sanders & Cairns, 2010; Wood et al., 2007). In contrast, Nordin (2014) did not find a link between presence and time perception. Yet other findings suggest that presence could enhance distance perception in a virtual world (Interrante et al., 2006; Ries et al., 2008; Mohler et al., 2008). It is therefore possible that presence could also enhance time perception in VR. However, to our knowledge, there is no empirical study that addressed this idea. Considering the mixed results in gaming studies and the lack of knowledge about the relationship between presence and time perception, we wanted to include measures of presence in our study and look at possible beneficial effects of presence on time perception. Therefore, we are the first to combine the effect of self-motion velocity on time perception with measures of presence. Insights into this relationship allow us to assess how presence in a virtual world is connected to the perception of time and if presence can contribute to an improved perception in IVEs.

2. Method

2.1 Participants

We recruited 26 participants, of which ten were male (age: M = 21.3 years, SD = 2.1 years) and sixteen were female (age: M = 21.1 years, SD = 1.9 years). All participants had normal or corrected to normal vision. Four participants (15.4%) reported having prior experience with HMDs. Sixteen participants (62%) were in possession of a driving license.

Participants were students from the University of Bern and received course credit in exchange to their participation. They provided written informed consent about taking part prior to the experiment and were debriefed after the experiment. They were treated in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the study was approved by the Ethics Committee of the Faculty of Human Sciences at the University of Bern.

2.2 Design and Material

The driving task consisted of six different temporal intervals (*2*, *3*, *4*, *5*, *6*, and *7* s) and five different velocities (*5*, *30*, *60*, *120*, and *240* kph) as well as a no motion condition (*0* kph). This resulted in 36 combinations of time and velocity, each of which was realized once, resulting in 36 trials per participant. The trials were presented in random order.

The dependent measures in the driving task were the time estimations (numerical estimation or reproduction, see procedure section for details), velocity, and distance estimations (both via visual analog scales). We also obtained presence and confidence ratings by using questionnaires. Confidence was assessed with a single item on an analog scale ("How confident are you about the correctness of your time judgments?"). For presence ratings the Pictorial Presence SAM (Weibel et al., 2015) and a questionnaire by Dinh et al. (1999) were used. The SAM consists of six sequences of five pictograms. The sequences represent different aspects of presence and the corresponding pictograms depict the intensity levels of presence. For each sequence, one of the pictograms that best fits the participants' subjective level of presence has to be chosen. The answer is then transformed into a number from one to five. The Dinh et al. questionnaire is comprised of ten questions that are accompanied by a Likert scale with five answer categories (*1* = poor, *5* = excellent). Additionally, participants have to indicate their subjective level of presence with a number from *1* to *100*, where *1* means having absolutely no presence at all and *100* means having as much presence as in the real world. The internal consistency of both presence scales was sufficiently high (Dinh et al. scale: Cronbach's Alpha = .82; SAM: Cronbach's Alpha = .74).

The virtual world was a long straight street, leading from a rural area into a city. There were no other cars in traffic and no human avatars on the sidewalk. The virtual model was provided by Esri Inc. (Redlands, United States) and used with permission. The experiment was run on the Vizard platform (WorldViz LLC., Santa Barbara, United States). The participants were seated on the co-driver's seat of a virtual car and they were facing forward. Apart from a steering wheel that was placed on the table next to the participants (Logitech G27, Logitech international S.A., Apples, Switzerland), no other props were used to emulate the virtual world in the laboratory room. Next to them was an avatar that appeared to drive the car. The participants themselves did not have a visible virtual body. During driving, sound effects of the inside of a car on the highway were played. The sounds were not matched to velocity and were the same in all conditions. Remarks of participants in pilot trials of the experiment indicated that this was not experienced as disturbing for the feeling of presence. Participants wore an Oculus Rift HMD (Oculus VR, LLC., Irvine, United States) and provided inputs by means of an Oculus Remote controller.

2.3 Procedure

After a short explanation of the task and the handling of the controller, participants put on the HMD and familiarized themselves with the virtual car interior. When they were ready, the experimenter started the task. Participants could from now on start a trial by pushing a button. In each trial, the car moved along the road with a certain velocity and duration. When the time limit was reached, the HMD screen turned black and the interior car sound effect ceased playing. Immediately afterwards participants reproduced the target duration by pressing a dedicated button on the controller once for beginning the reproduction interval and once for stopping it. There was a short auditory feedback whenever the button was pressed. The participants were instructed to reproduce the duration from the beginning of the car motion until the fade out of the screen. After the reproduction, participants were presented with a series of input screens, where they had to give an estimate of the duration, velocity and traveled distance of the car ride. The numerical time estimation had to be given by choosing a value from a list with a range of 1 to 9 s in intervals of 0.5 s. Participants were advised to rely on their feeling of time. The other estimates were given on visual analog scales reaching from 0 to 300 kph (velocity), and 0 to 600 m (distance). Throughout the reproduction and judgment phase, the background remained black and only input screens were visible. After finishing the estimates, the participants found themselves back in the car at the same starting position as before. They were now able to start the next trial. After half of the trials, participants were given the chance for a short break. At the end of the last trial, they had to give a self-evaluation of their performance in the time reproduction task (see design and material section above). Hereby the visual analog scale ranged from *0% confidence* to *100% confidence*. At the end of the task, participants were asked to fill out two presence questionnaires on the computer.

3. Results

Descriptive statistics of the dependent variables are depicted in Table 1. Overall, target durations were underestimated with numerical estimation and reproduction as dependent measure. Both measures were positively correlated, $r(930) = .58$, $p < .001$. We observed a response bias resembling the Vierordt's law (Woodrow, 1951): Shorter durations were overestimated and longer durations were underestimated in comparison to the overall subjective mean estimation error (see Fig. 1). Overall, target velocities were underestimated, only the 5 and 30 km/h target velocities were slightly overestimated (see Fig. 2). Distances were generally overestimated, except for the three longest distances, which were underestimated (see Fig. 3). Time judgments were positively associated with velocity judgments (numerical estimation: $r(930) = .26$, $p < .001$; reproduction: $r(930) = .14$, $p < .001$) as well as with distance judgments (numerical estimation: $r(930) = .33$, $p < .001$; reproduction: $r(930) = .25$, $p < .001$). Adjustments using Bonferroni's method and bootstrapping (1000 samples) were performed in order to obtain values of significance. Furthermore, we obtained similar levels of presence as in previous studies (Dinh et al., 1999; Hendrix & Barfield, 1996a; Hendrix & Barfield, 1996b; Weibel et al., 2015; Wissmath et al., 2010).

To obtain measures of subjective time relative to elapsed time, we calculated the ratio of estimated or reproduced duration divided by the target duration, for each trial. We refer to this measure as *subjective duration*. A resulting value of one means that the target time was judged accurately, a value above one that time was overestimated, and a value below one that time was underestimated. We found a positive relationship between target velocity and subjective duration for numerical estimation ($r_\tau = .14$, $p < .001$; Fig. 4) and reproduction ($r_\tau = .08$, $p = .001$; Fig. 5). This was in accordance with Hypothesis 1: higher target velocities were associated with longer subjective time. To assess the linearity of the effect of velocity (Hypothesis 2), we implemented a linear contrast analysis that was adjusted for the unequal spacing of target velocities. The linear contrast was significant for both numerical estimation ($F = 51.24$, $p < .001$) and reproduction ($F = 31.41$, $p < .001$), supporting Hypothesis 2.

In addition to measures of association, we calculated a multilevel model with *target velocity* as a factor and *target duration* as a linear predictor to adjust for both the factorial structure and the nested layering of the data (cf. Goldstein, 2011; Raudenbush & Bryk, 2002). We included *participants* as a second-level variable and used it to specify a random intercept and a random coefficient for the factor *target velocity*. The dependent variable was the *subjective duration* in terms of *numerical estimation* and *reproduction*. The analysis was performed with the *mixed* function from the *afex* package in *R*, using maximum likelihood estimation (Singmann et al., 2015). We observed a significant main effect of target velocity on numerical estimation, $\chi^2(5) = 23.10$, $p < .001$, and reproduction, $\chi^2(5) = 16.20$, $p = .006$. Faster velocity conditions elicited longer subjective time ratings than slow velocity conditions. This was, again, in accordance with Hypothesis 1. There was also a negative effect of target duration on numerical estimation, $b = -0.022$, SE = 0.003, $p < 0.001$, and reproduction, $b = -0.036$, SE = 0.004, $p < 0.001$. In both cases, there was no significant interaction between target duration and velocity (both $p > .05$). To again test for the linearity of the effect of target velocity, a model comparison between the above model where velocity was entered as a factorial variable and an additional model where it was entered as a continuous variable was initiated. The model with the continuous variable did not improve model fit (numerical estimation: $\chi^2(26) = 10.08$, $p = .998$; reproduction: $\chi^2(26) = 34.63$, $p = .120$). Thus, the linearity assumption received no support in the multilevel analysis. This conflicts with Hypothesis 2.

Taken together, the results were in accordance with Hypothesis 1 and partly in support of Hypothesis 2. There was a linear relationship between target velocity and subjective time in the association measures. Additionally, there was a positive but non-linear relationship between target velocity and subjective time in the multilevel analysis, which adjusted for the nested factorial structure of the data. Figures 4 and 5 show that the fitted curves decline in the two highest velocity conditions, indicating possible deviations from linearity.

To test our assumptions about presence, we analyzed the associations between presence ratings and time judgments. Adjustments using Bonferroni's method and bootstrapping (1000 samples) were performed in order to obtain values of significance. There was no correlation between presence and mean subjective time in numerical estimation (Dinh et al. scale: $r(24) = -.22$, $p = .541$; SAM: $r(24) = -.04$, $p = 1$) and reproduction (Dinh et al. scale: $r(24) = .12$, $p = 1$; SAM: $r(24) = -.03$, $p = 1$). This means that the individual level of presence was associated with neither overestimation nor underestimation of time compared to the overall mean estimation of the sample. To test if presence was connected to performance in time judgments, we needed to calculate the accuracy of time judgments. Accuracy was defined as the absolute difference between target duration and numerical estimation or reproduction. Presence was not associated with accuracy in numerical estimation (Dinh et al. scale: $r(24) = .09$, $p = 1$; SAM: $r(24) = -.13$, $p = 1$) and reproduction (Dinh et al. scale: $r(24) = .12$, $p = 1$; SAM: $r(24) = .15$, $p = .919$). Presence ratings were also not associated with accuracy in velocity and distance judgments (all $p > .05$). Interestingly, presence ratings were also not associated with confidence ratings (Dinh et al. scale: $r(24) = .09$, $p = .657$; SAM: $r(24) = .27$, $p = .184$). Furthermore, confidence ratings did not show associations with accuracy of time judgments (numerical estimation: $r(24) = -.17$, $p = .420$; reproduction, $r(24) = -.02$, $p = .930$). The maximally observed power for these analyses was

0.31. The results did not support our proposition: higher levels of presence did not lead to better performance in the time judgment task.

4. Discussion

In this experiment, we tested whether the velocity of one's own body motion influenced the perception of time. The results showed longer time judgments in conditions with high velocities compared to conditions with low velocities. This confirms the effect of self-motion on time judgment as reported by Brehmer (1970) and van Rijn (2014). The subjective duration of self-motion trials increased with each increase in velocity. However, contrary to our expectations, this increase is not linear. A linear effect of velocity was reported in studies using stimulus motion (Brown, 1995; Tomassini, et al., 2011). The multilevel analysis suggests deviations from a linear effect of velocity. Especially the effects of the two high velocity conditions (120 and 240 kph) were not as pronounced as expected. This is in line with the study by van Rijn (2014), in which the fast self-motion condition was weaker compared to what would be expected from a linear prediction. The data by Brehmer (1970) were not suitable for testing a linear effect of velocity. At this point, we have no explanation why self-motion does not elicit the same linear effect as stimulus motion and whether linearity is always absent in the effect of self-motion. Future studies using self-motion paradigms are needed to provide answers to these questions. Apart from the linearity assumption, we were able to demonstrate a monotonic positive relationship between self-motion velocity and subjective time, thereby confirming previous work. Not only the observation of fast moving stimuli leads to longer time judgments but also the overall motion of the surroundings from a first-person perspective. These results are in accordance with the assumption that subjective time can be affected by sensory input.

Specifically, the faster the virtual surroundings changed, the longer was the subjective impression of time. This could be explained by an internal clock model in which the timekeeper mechanism is accelerated by sensory input. A state-dependent-network model could also serve as an explanation. Fast changes in visual input correspond to large changes in activation patterns, which in turn lead to a lengthening of subjective time. Roseboom et al. (2019) proposed yet another mechanism according to which subjective time is explained in terms of changes in perceptual content. In this model, no internal clock or activation pattern is necessary. Instead, changes in visual content directly lead to temporal information that can be used to provide a subjective duration judgment. In our experiment, this would imply that the speed of a trial was effectively equal to the rate of change in visual content, which could be detected by the visual system and transformed into a behavioral response.

It has been argued in the literature (e.g. Casasanto & Boroditsky, 2008; Lambrechts et al., 2013, Riemer et al., 2018) that there is an asymmetric relationship between time and space judgments: space perception strongly influences time perception but not necessarily vice versa. In our experiment, there was an overall underestimation of time and velocity but an overall overestimation of distance. Thus, the judgments of the participants seemingly conflicted with physics (if time is shorter and velocity is lower, then also distance is by necessity shorter). Nonetheless, there was a significant positive relationship between time and distance judgments, suggesting that time judgments could indeed be influenced by distance judgments. With our experimental setup, it is not possible to assess the direction of causality and to decide whether space perception influenced time perception more strongly than vice versa. Interestingly, however, the supposed violation of physical laws seems to be based on the fact that there was also a positive correlation between time and velocity judgments. This suggests that – contrary to physics – higher velocity judgments were connected to longer time judgments. Therefore, the suggested coupling of magnitudes in our experiment was not consistent with real life, which challenges the assumptions of the ATOM model.

We used an IVE to control the attentional demand between moving and non-moving conditions and maintain a high level of external validity. Furthermore, we could implement motion without any motor effort or ramp-up phase. Additionally, we extended previous findings to explicit measures of time and time reproduction. Both measures were influenced in the same way by velocity of self-motion as shown earlier by magnitude production (Brehmer, 1970) and magnitude comparison (van Rijn, 2014). Thus, self-motion velocity does indeed affect our subjective impression of time. Our experiment is the first demonstration in which a VR setup was used to induce self-motion in a time perception task and we could therefore demonstrate that the effect is also applicable to immersive virtual worlds and thus computer games.

Furthermore, we proposed that the presence level could affect performance in the time judgment task. However, this proposition was not supported: presence was not associated with performance in the time judgment task and no relation between presence and confidence ratings was observed. We also did not observe a general decline in the magnitude of time judgments with increasing levels of presence. Since aggregated data were used to assess these relationships, statistical power was low due to the small number of data points in the aggregated variables (n = 26, i.e. number of participants). Thus, we can only rule out a strong effect of presence on performance in our data. Previous findings reported a beneficial effect of presence on spatial perception (cf. Interrante et al., 2006; Ries et al., 2008; Mohler et al., 2008). However, there could be no such effect or a smaller effect for temporal perception. The flow of time is potentially the same in the real world and IVEs whereas there are substantial differences in the configuration of space (resolution, extent of details, field of view, etc.). Thus, the level of presence did not play a significant role in the prospective judgment of time intervals in an IVE. Nevertheless, it is also possible that the connection between presence and the judgment of visual characteristics (i.e. distances) is simply *stronger* than the connection between presence and the judgment of temporal characteristics. Another possibility is that presence plays a minor role for the judgment of short intervals and only affects subjective time on a larger scale.

There is one limitation to consider in our experiment: the amount of visual information of a trial is confounded with its target duration and velocity. For example, in long and fast trials, participants saw more aspects of the virtual world than in short and slow trials (i.e. buildings and street crossings). This limitation also applies to previous studies of self-motion. To distinguish between the amount and velocity of visual information in future studies, we suggest inducing basic optic flow in VR environments. For example, dot clouds could be used to hold the amount of unique visual information constant while manipulating the velocity of the dots. We implemented an immersive environment in our study in order to remain close to real life driving situations.

Results from this study have clinical and practical implications. For example, insights into the relationship between motion and subjective time could support the design of serious games intended for reducing the subjective duration of unpleasant experiences such as dental operations or prolonged periods of waiting. For instance, our results show that, surprisingly, fast-paced racing games could be less efficient in inducing time loss. Additionally, our results show that the design of windows on long-distance flights or train rides could affect the subjective duration of the journey: subjective time is affected by motion of the surroundings. Conceivably, virtual displays could be used to affect the subjective time experience. Another application is the subjective perception of speed in real-life driving. We showed that fast driving resulted in an overestimation of time. Potentially, drivers are tempted to exceed the speed limit in zones with an already high limit, in order to compensate for the subjective longer duration (cf. van Rijn, 2014).

To sum up, our findings show that increased velocity of self-motion induced by vection, leads to an overestimation of short time intervals. This was true for both measurements, reproduction and direct numerical estimation. The amount of presence experienced in the virtual world did not influence the magnitude of time judgments or the accuracy of time judgments. Unlike the perception of space, the flow of time depends less on the characteristics of the virtual world, and thus, there was no effect of presence on time perception in VR.

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Tables

Table 1.

Descriptive statistics of the dependent variables

Variable	Minimum	Maximum	*M*	SD
Numerical estimation of time	-6000 ms	4000 ms	-794 ms	1414 ms
Reproduction of time	-6756 ms	4494 ms	-812 ms	1204 ms
Estimation of velocity	-215 kph	180 kph	-21 kph	52 kph
Estimation of distance	-400 m	367 m	33 m	78 m
Self-confidence rating	10.45%	86.93%	53.64%	18.97%
Presence SAM	2.83	4.50	3.53	0.44
Presence Dinh et al. subjective	20%	95%	51.15%	21.86%
Presence Dinh et al. scale	1.70	4.00	2.84	0.57

Note: For all estimation variables, differences between the actual value and the estimated value are displayed.

Figures

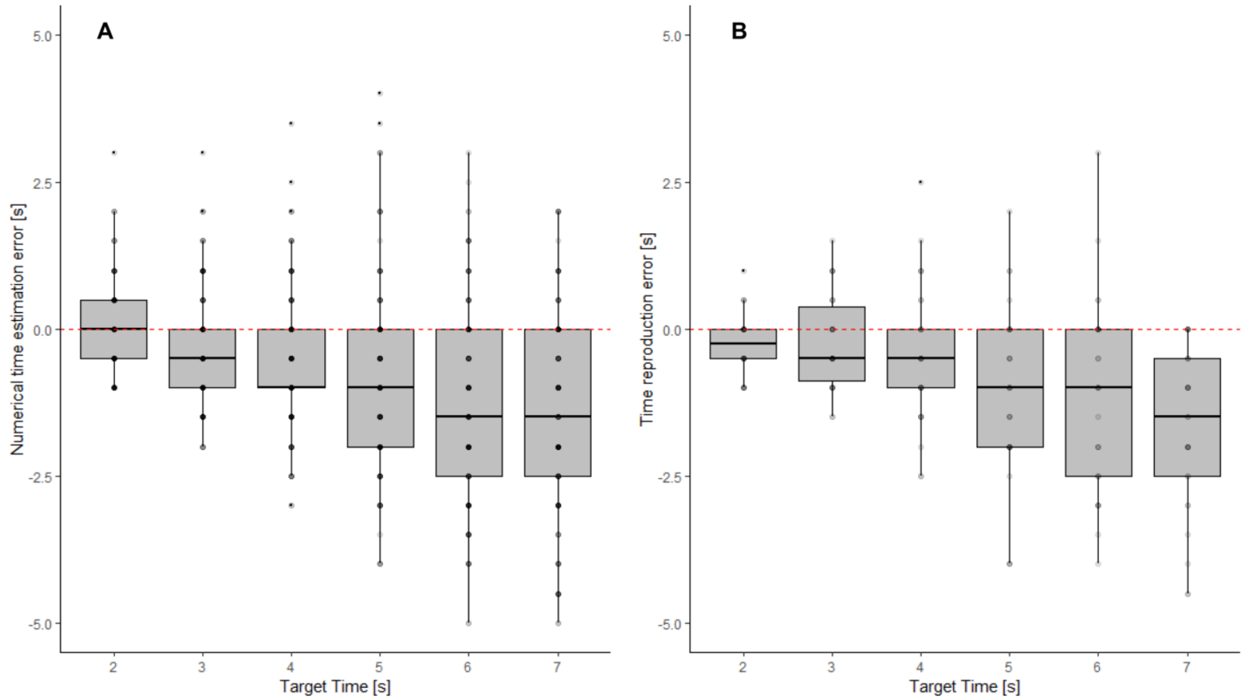

Figure 1. Panel a) shows the numerical time estimation error and panel b) the time reproduction error as a function of target time. Both measures are defined as the difference between target time and estimated time. Red dotted lines indicate veridical judgments

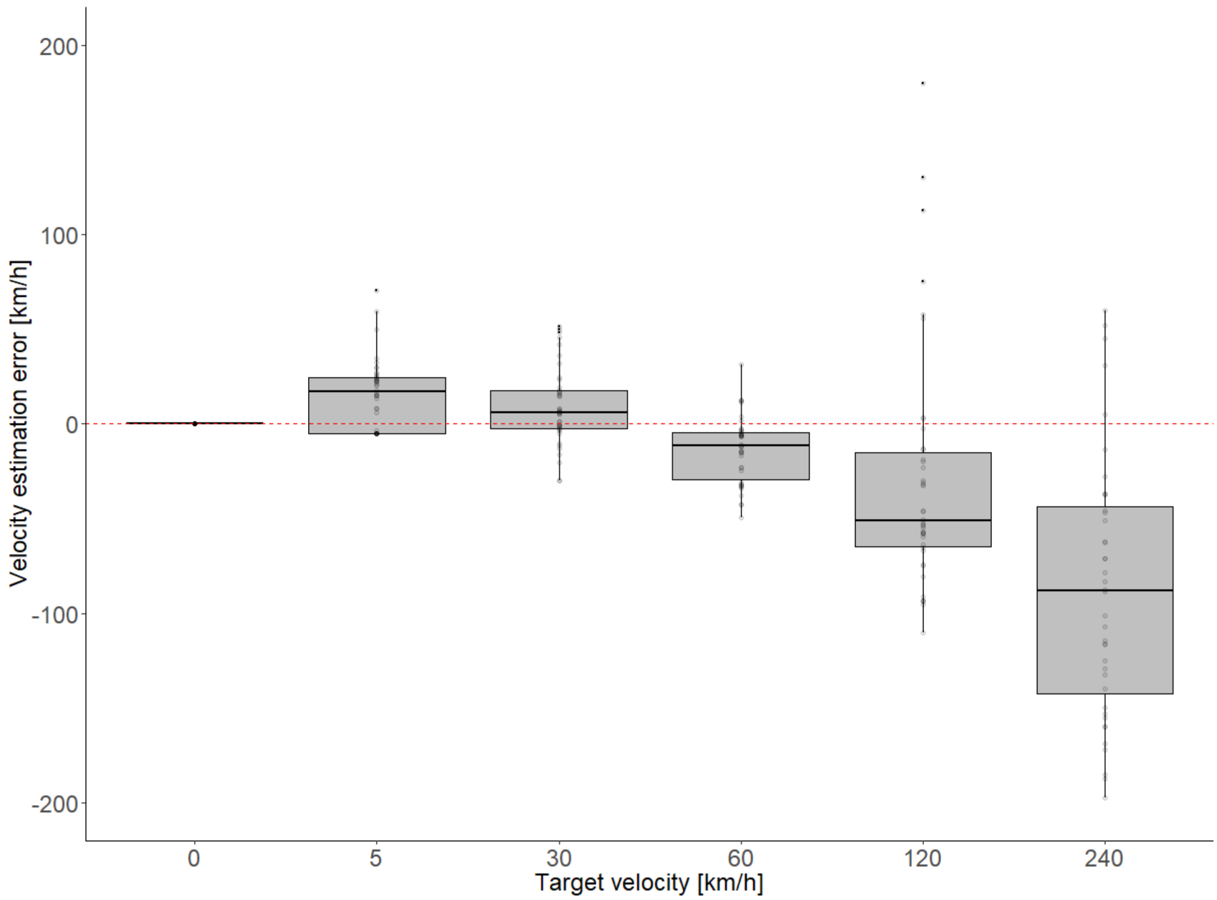

Figure 2. Velocity estimation error as a function of target velocity. Velocity estimation error is defined as the difference between target velocity and estimated velocity. The red dotted horizontal line indicates veridicality

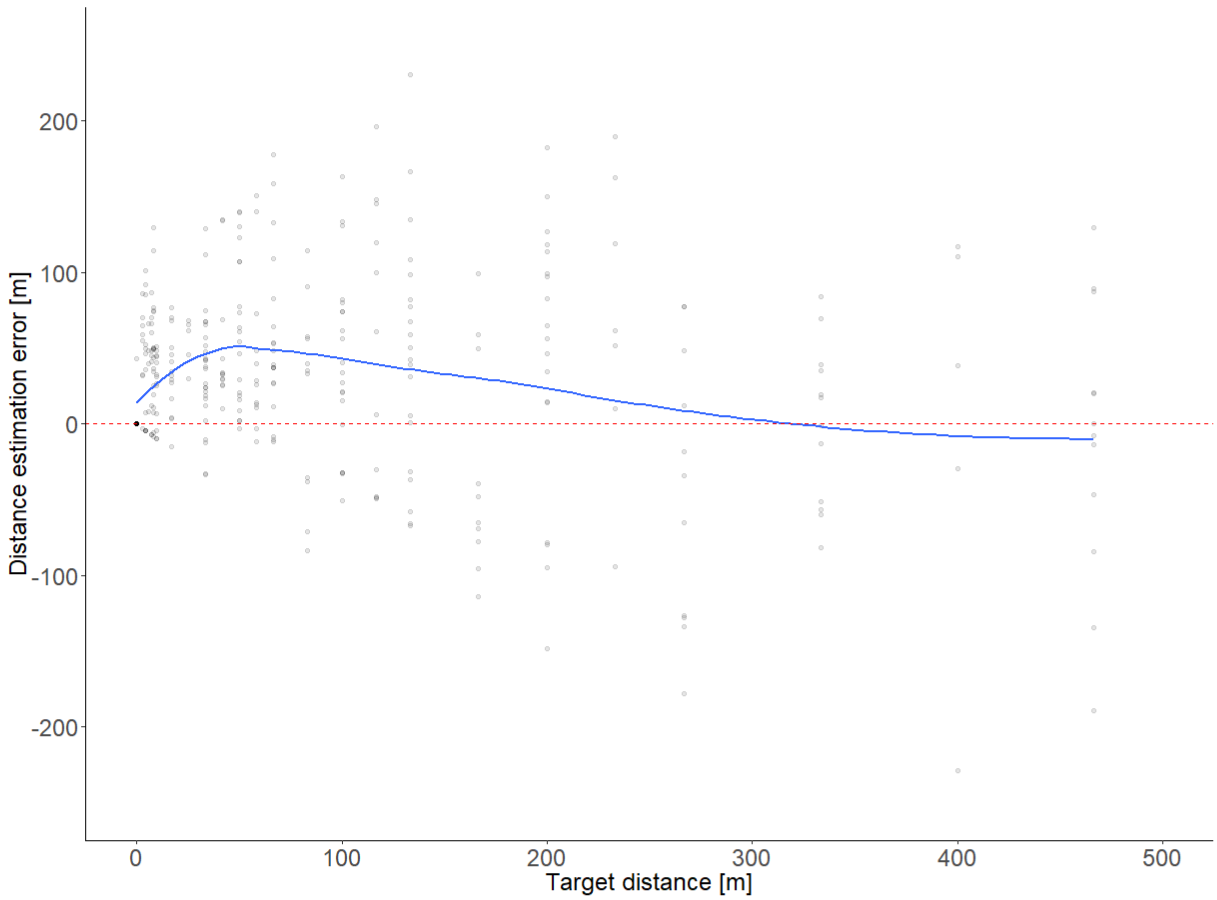

Figure 3. Distance estimation error as a function of target distance. Distance estimation error is defined as the difference between target distance and estimated distance. The target distances result from all possible combinations of target times and target velocities. Distances are therefore pictured as a continuous variable. The red dotted horizontal line indicates veridicality. The blue line expresses the relationship between the variables as a loess curve

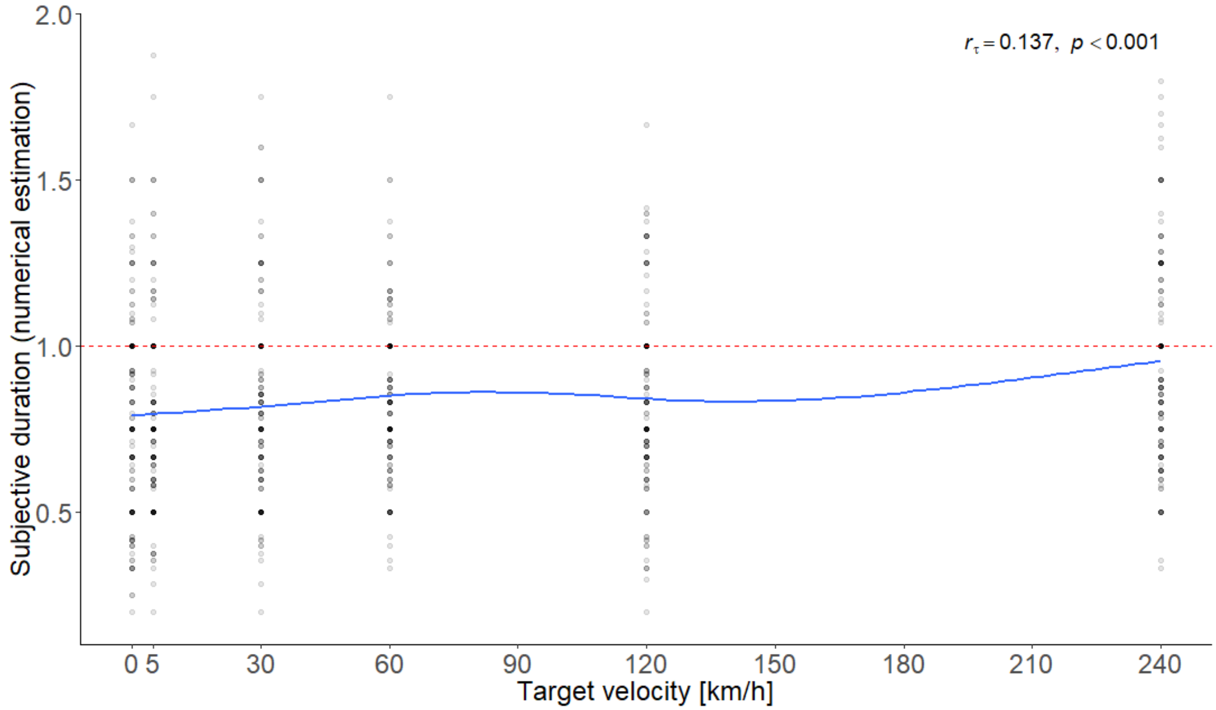

Figure 4. Relationship between target velocity and subjective duration for numerical estimation. Subjective duration is calculated by dividing the estimated value by target time. Therefore, values above one indicate overestimation and values below one indicate underestimation. The dotted red line indicates veridical judgment. The blue line expresses the relationship between the variables as a loess curve

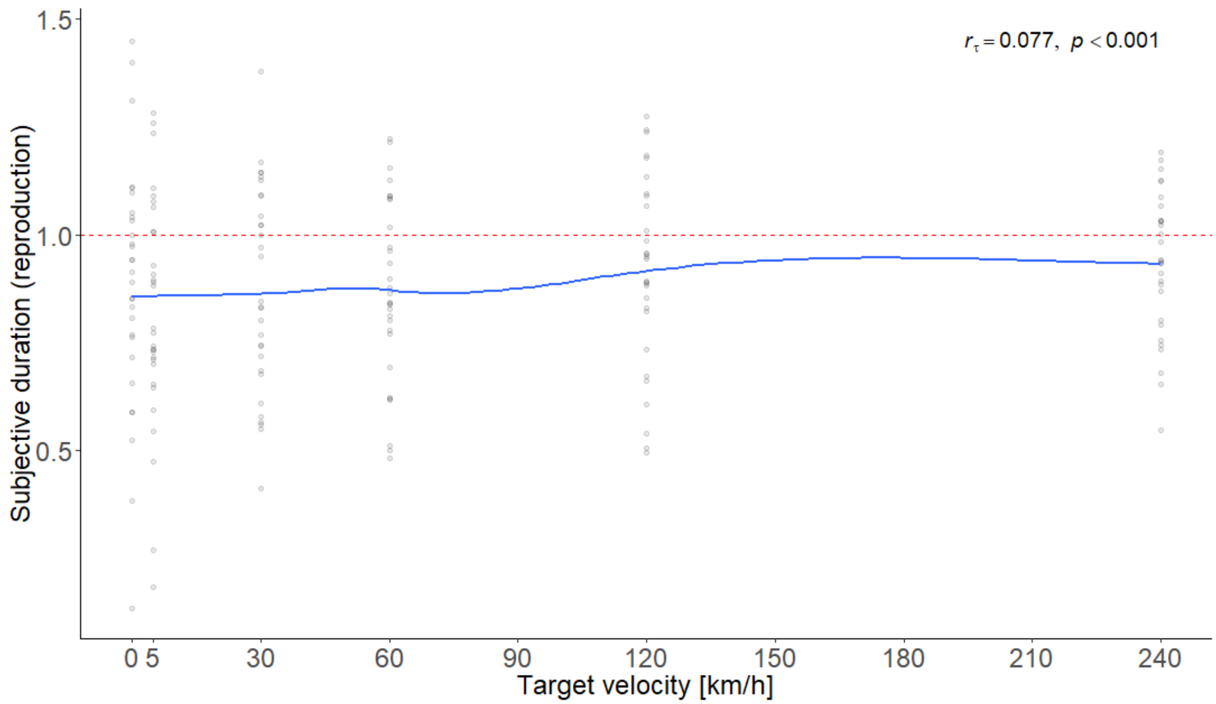

Figure 5. Relationship between target velocity and subjective duration for reproduction. Subjective duration is calculated by dividing the estimated value by target time. Therefore, values above one indicate overestimation and values below one indicate underestimation. The dotted red line indicates veridical judgment. The blue line expresses the relationship between the variables as a loess curve

Figure Captions

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