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Time flies when you're having flow: An experiment on time perception and challenge in a VR game

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ABSTRACT

Behavioural measures of flow state have not yet been identified. Instead, flow state has traditionally been measured using retrospective self-reports that rely on memory ability and are vulnerable to reporter bias. In our study, we examined if altered time perception can be observed during flow state by measuring temporal processing both during and after an activity. Seventy healthy young adults played the virtual reality game 'Beat Saber' with three challenge levels (easy, medium, and hard) in a repeated-measures design. We predicted the medium condition would induce flow due to the balance between participant skill and challenge, leading to time being reported as passing faster than easy and hard conditions. We also measured self-reported flow experience, emotions, objective task performance, and heart rate/variability (HR/HRV). Time perception was measured both concurrently (during gameplay) by participants verbally signalling the passage of 50-s intervals, and retrospectively (after gameplay) through session duration estimates. Consistent with previous flow research, the medium-challenge condition was associated with the highest levels of subjective flow and lowest levels of negative emotions. HR increased and HRV decreased as challenge increased. Notably, there was a significant relationship between concurrent time perception and flow experience. Participants in the medium-challenge (flow) condition perceived 50-s intervals as significantly shorter than in the easy and hard conditions, indicating that flow in our experiment was associated with time acceleration. Measuring concurrent time perception therefore provides an objective alternative to retrospective self-report when measuring flow states.

1Introduction

Flow has been defined as an optimal mental state of energized focus and involvement. Flow makes an activity feel automatic and enjoyable and is motivating without external reward (Abuhamdeh, 2020; Csikszentmihalyi, 1990). It is a subjective state of deep involvement and absorption that people report when they experience activities that are comfortably challenging. The perceived balance between the person's skill and the level of challenge they are confronted with, the so-called skill-challenge balance, is one of the most salient features of flow (Norsworthy et al., 2021). If an activity lacks challenge relative to skill, the under-challenged person will become bored. Conversely, if the challenge is too high, the over-challenged person will become anxious or frustrated, leading to lack of flow in both cases (Nakamura & Csikszentmihalyi, 2002). It thus follows that video games with mechanics that facilitate skill-challenge balance can induce flow (Fullagar et al., 2013; Sweetser & Wyeth, 2005; Yu et al., 2023). This skill-challenge antecedent should consequently lead to flow-induced enjoyment and an altered perception of time.

Losing track of time when playing videogames is a widespread phenomenon (Bisson & Grondin, 2013; Luthman et al., 2009; Rau et al., 2006; Tobin et al., 2010) and is often seen as an indicator of positive game experience (Wood et al., 2007). Altered time perception is a key feature of flow and flow is thought to be a main driver of changes in temporal processing while playing video games (Rutrecht et al., 2021). This alteration of time perception may be attributed to attentional shifts.

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When focusing most of their attention on a game, a player will have less attentional resources to keep track of time (Tse et al., 2004). It is important to note that perception of time during flow experiences was originally considered bidirectional, meaning it could either accelerate or decelerate relative to true time (Jackson & Marsh, 1996; Sweetser & Wyeth, 2005), so that "hours can pass in minutes and minutes can look like hours" (Csikszentmihalyi, 1990, p. 3). In recent years, most researchers have come to agree that time seems to accelerate when experiencing flow (Nuyens et al., 2020), which may cause a player to feel as if a 1-h gameplay session only took 20-min. The reason for a time underestimation rather than overestimation during flow may be due to a positive appraisal of the activity, i.e., the player finds it enjoyable and does not necessarily want it to end (Nuyens et al., 2020). This is supported by the opposite scenario, in which under-stimulating or unpleasant experiences make time seem to drag, leading to overestimations of the time spent on these activities (Campbell & Bryant, 2007; Im & Varma, 2018).

Despite research on time perception and flow in games, only two studies have examined this relationship in an experimental setting. First, Keller and Bless (2008) performed two experiments in which participants played 'Tetris' in one of three challenge conditions related to the speed of blocks falling (boredom, adaptive, and overload, p. 201), asking them to self-report their playtime on a 10-point scale ranging from 'very short' to 'very long'. In both experiments, the adaptive (flow) condition resulted in an accelerated sense of time passing, and a stronger subjective experience of flow. More recently, experiments with a Virtual Reality game by Rutrecht et al. (2021) also indicated that subjective flow experience was associated with accelerated time passage when measured on a ten-point scale, ranging from 'very slowly' to 'very fast'. However, when participants were asked to retrospectively quantify the duration of the play session in minutes and seconds, there was no significant underestimation (i.e., regardless of flow, participants estimated the 25-min gameplay session to have lasted 24 min, on average). Therefore, even though these experiments showed that flow states led to subjective feelings of time acceleration, neither of these studies found any actual differences in time estimates.

Flow is characterized by nine dimensions (Nakamura & Csikszentmihalyi, 2002). The perceived skill-challenge balance is the most-used dimension within flow research (Fong et al., 2015; Norsworthy et al., 2021) and is considered to be the primary antecedent that facilitates entering flow state (Engeser & Rheinberg, 2008). If the challenge is too high compared to the skill level, the person will feel anxious and frustrated, whereas if the challenge is much lower than the skill level, boredom will ensue (Csikszentmihalyi, 2000). Video games are featured heavily in flow research because they can provide a continuous balance between skills and challenges (Cowley et al., 2008; Nuyens et al., 2020; Sweetser & Wyeth, 2005). The balance between skill and challenge has been investigated in relation to video game-induced flow in numerous ways: conceptionally (e.g., Chen, 2007; Sherry, 2004), cross sectionally (e.g., Hamari & Koivisto, 2014; Jin, 2012) experimentally (e.g., Keller et al., 2011; Schmierbach et al., 2014), and more recently in Virtual Reality (Lemmens & von Münchhausen, 2023; Tian et al., 2017; Yu et al., 2023).

When video games provide an optimal level of challenge, both flow and enjoyment are likely to occur (Lazzaro & Keeker, 2004; Sweetser & Wyeth, 2005). In fact, flow and enjoyment when gaming appear to be reciprocally related (Ihamäki, 2014; Lemmens & von Münchhausen, 2023; Tozman et al., 2015). Because men generally find games more enjoyable, exciting, and sufficiently challenging, they are more likely to experience flow than women, who are more likely to find games more difficult or complex (Sherry, 2004). Survey studies have identified these gender differences in the experience of flow while playing games, with men reporting higher levels of flow than women (Lee, 2009; Voiskounsky & Wang, 2014). Experiments have also indicated that men generally perform better at games than women (Brown et al., 1997; Lemmens & von Münchhausen, 2023). These performance differences may disproportionately affect game enjoyment among women, as research has shown that men's enjoyment of a game was not influenced by objective game performance while women's enjoyment was (Hopp & Fisher, 2017). The role of gender must therefore be considered when examining the interrelations between performance, enjoyment, and flow.

When experiencing flow, the enjoyment associated with an increase in dopamine appears to accelerate a person's internal clock, making them feel that 'time flies' (Agarwal & Karahanna, 2000; Simen & Matell, 2016). A recent review on video games and time perception concluded that despite a lack of studies examining the causal link between game enjoyment and time perception, it was plausible that having 'fun' (i.e., a positive game experience) leads to underestimating time duration (Nuyens et al., 2020). Conversely, feelings of boredom and frustration, as opposed to flow, can cause a person to feel as if time is passing slower, leading to overestimation of time duration (Im & Varma, 2018). Additionally, as flow is considered a state of heightened awareness that stimulates optimal performance (Jackson & Csikszentmihalyi, 1999), flow state should lead to better game performance. Indeed, participants achieved higher scores on Pac-Man when in a state of flow (Engeser & Rheinberg, 2008), and performance on two different VR games was positively correlated with flow states, indicating that stronger flow experiences were related to better gameplay performances (Lemmens & von Münchhausen, 2023; Rutrecht et al., 2021). Therefore, the current literature suggests relationships between flow, time perception, enjoyment, and performance.

It is currently unclear whether measures of physiological arousal such as heart rate (HR) and heart rate variability (HRV) can be used as objective indicators of flow because the interrelations between physiological arousal, flow, and the skill-challenge balance show inconsistent results (Bian et al., 2016; Keller et al., 2011; Khoshnoud et al., 2020; Peifer et al., 2014). Two studies found that HR was higher in both medium and hard gameplay conditions compared to the easy condition (Harmat et al., 2015; Lemmens & von Münchhausen, 2023), indicating that both flow and frustration may cause an increase in physiological arousal, whereas 'boring' (low challenge) gameplay reduces physical excitement. Several other studies have found that players' heart rate increased as challenge increased (easy, medium, hard) when playing various versions of Tetris and Pong (Chanel et al., 2017; De Sampaio Barros et al., 2018; Tian et al., 2017). Similarly, several studies have shown that HRV decreased as challenge increased, with the highest HRV (i.e., lowest arousal) in the easy condition, moderate HRV in the medium condition, and lowest HRV in the hard condition (Tian et al., 2017; Tozman et al., 2015). These findings indicate that a stronger sense of flow while playing is related to higher physiological arousal when compared to under-challenged (easy) gameplay sessions, yet the arousal may not be higher than the over-challenged (hard) session. Regardless, physiological arousal appears an imprecise indicator of flow state, and it seems necessary to triangulate with other measures, such as time perception (Clark, 2023).

A key issue in current flow research is the heavy reliance on retrospective self-reports. Self-reported survey scales can be problematic because they are subject to biases in participant reporting and memory (Brenner & DeLamater, 2016) and require a deep level of introspection (Weber et al., 2017). Stopping a participant's gameplay or periodically asking questions while playing could break the potential flow state researchers are trying to assess. Furthermore, self-report survey scales do not work well for young children or those with communication challenges (Inal & Cagiltay, 2007; Redelmeier & Kahneman, 1996). When self-report measures are not practical or optimal, flow has sporadically been assessed using behavioural observations (Tordet et al., 2021), or increasingly through physiological measurements, although these have yielded mixed results (Dietrich, 2004; Keller et al., 2011; Peifer et al., 2014). There is a clear need for valid and reliable methods to measure flow during an activity, that are more inclusive, do not disturb the participant and are practical for researchers.

Considering that video game players frequently experience time passing more quickly during a state of flow, our study examined whether altered time perception, a key feature of flow, could be assessed *during* a flow-inducing activity (concurrent time assessment) in addition to the traditional approach of measuring time perception *after* the activity has ended (retrospective time assessment). To this end, we wanted to investigate potential relationships between concurrent and retrospective time alteration and other flow measures. The overarching rationale was to create a methodological advancement that may offer a way to identify behavioural signatures of flow that could later be tested among non-verbal subjects including non-human animals (Clark, 2023; Taylor et al., 2022). For that purpose, a VR game within-subjects experiment with three challenge levels was conducted among 70 healthy young adults to test the following hypotheses:

Hypothesis 1: Gameplay during the easy condition will be linked to (a) reduced flow, (b) increased boredom, (c) reduced enjoyment, (d) decelerated perceived passage of time, and (e) lower heart rate and higher heart rate variability, compared to the medium condition.

Hypothesis 2: Gameplay during the hard condition will be linked to (a) reduced flow (b) increased frustration, (c) reduced enjoyment, and (d) decelerated perceived passage of time, compared to the medium condition.

2. Method

2.1. Sample

Sample size was based on detecting a potentially small effect size of $F = 0.25$, in a within-between interaction ANCOVA repeated-measures design. Power analysis was conducted using G*Power, resulting in a minimum sample size (at least $p < .05$) of $N = 54$. An experiment was conducted involving 70 English-comprehending students recruited from the University of Amsterdam, aged between 18 and 34 years old ($M = 20.46$, $SD = 2.21$). In our sample, there were 38 men (54.3 %) and 32 women (45.7 %), none of the participants self-identified as non-binary or other. 85.7 % of the participants had a little prior experience of VR gaming, 11.4 % had some prior experience, and 2.9 % indicated that they played VR games regularly over the last few years. Before the experiment, all participants provided informed consent, confirmed that they were in good physical and mental health, and reported no significant cognition, learning, memory, or hearing impairments, nor a clinical diagnosis of depression. They confirmed they did not have photosensitive epilepsy or other sensitivity to flashing lights and were willing to wear a VR headset and heart rate monitor with a chest strap for approximately 60 min during one period of testing. Participants received course credit for participating in the experiment.

2.2. Manipulation

Beat Saber (Beat Games, 2019) is a rhythm-based VR 'exergame' that blends physical exercise with gaming elements (Szpak et al., 2020). In the game, players need to hit a series of virtual blocks with virtual sticks ('sabers') as the blocks approach. The challenge level is determined by the rhythm and spatial complexity of the sequence of approaching blocks (Huber et al., 2021). The combination of physical activity and music in VR games reduces distractions and is known to facilitate flow (Dongas & Grace, 2023; Lemmens & von Münchhausen, 2023). The number, properties, and locations of blocks in each session were set by the researchers. Three gameplay sessions with different challenge settings were applied to each participant: The easy condition included 107 blocks (an average of 13 blocks per minute), the medium condition featured 1249 blocks (an average of 147 blocks per minute) and the hard condition consisted of 3216 blocks (an average of 379 blocks per minute). The three conditions easy (A), medium (B), and hard (C) were presented in six counterbalanced session orders: ABC, ACB, BAC, BCA, CAB, and CBA. The song used for each condition in this experiment was *Mii Channel Theme* by Kazumi Totaka, 2008 (duration 2:06, 131 bpm), chosen primarily because it is instrumental and lacks overly strong rhythms and catchy melodies which could impact participants' emotional and physiological responses (Cook et al., 2019). Each condition (A, B or C) lasted exactly 8 min and 28 s because the song was looped four times.

2.3. Procedure

The experiment was approved by the ethical committee from the department of Communication at the University of Amsterdam (reference: FMG-7824). After participants provided informed consent, the researcher verbally explained the rules of Beat Saber. Participants were instructed to apply a heart rate monitor on their chest (*Polar H1*0 ECG) and were aided in putting on the VR headset (Valve Index). First, they played a tutorial level, featuring the song ***$100 Bills*** by Jaroslav Beck, 2018 (duration 2:18, 105 bpm) to practice and familiarize themselves with the mechanics and controls of the game. Their performance during the tutorial was measured, as was their baseline HR and HRV. After a 5-min break, each participant played three game sessions with three different challenge levels in counterbalanced order. HR and HRV were recorded during each condition. Between each session, participants took off the VR headset and filled out a short questionnaire with statements about time perception, flow experience, frustration, boredom, and enjoyment. Thus, they completed three questionnaires with identical questions immediately after each of the three gameplay sessions. The last questionnaire also included questions on age, gender, and VR experience. Additionally, performance in each gameplay session was assessed through their game score and ranking.

2.4. Measures

2.4.1. Subjective flow experience

Game flow was assessed after each session through a self-report questionnaire including nine adapted statements based on the nine dimensions of flow experience (Csikszentmihalyi, 1990; Fang et al., 2013; Jackson & Marsh, 1996), using a 5-point Likert scale to rate agreement on each of the following items: 1) I knew exactly what I needed to do; 2) I was aware of how well I was performing; 3) I kind of forgot about myself while playing; 4) I found myself acting automatically without having to think; 5) I lost track of time; 6) This provided a good test of my skills; 7) Playing felt like a rewarding experience in itself; 8) I was totally concentrated on what I was doing; 9) I felt comfortable with the controls of this game. The scale showed acceptable reliability in the easy and medium conditions (easy: Cronbach's Alpha 0.71 ($M = 3.22$, $SD = 0.58$; medium: Cronbach's Alpha 0.66 ($M = 3.85$, $SD = 0.48$) and borderline acceptable reliability in the hard condition (Cronbach's Alpha 0.62 ($M = 3.45$, $SD = 0.54$).

2.4.2. Retrospective session duration estimate

After completing each session, participants were asked to estimate the total duration of that condition using a slider ranging from 5 to 15 min, with ten decimal positions between each minute. Participants were told that each session had a random duration between 5 and 15 min, whereas all sessions actually had exactly the same length (8 min and 28 s). Participants' mean time estimates across gameplay sessions was 8.96 min ($SD = 2.27$), indicating their estimates were generally slightly longer than the actual duration of the sessions (8 min, 28 s = 8.47).

2.4.3. Concurrent time interval task

Participants were instructed to loudly say the word 'Beats' at 50-s intervals throughout each session. 202 gameplay videos (8 videos were missing due to various errors) were uploaded to a private YouTube account to generate subtitle text files (.srt) with timestamps; these were subsequently downloaded and analysed (videos were then deleted from YouTube). Initial analyses indicated that many words similar to *Beats* that were present in the subtitle files were in fact faulty transcriptions of the spoken word *Beats* and therefore subsequently coded as such (e.g., *be, pea, bit, eat, peats, peace, bats, beets, it's, he's*). All other words in the subtitles (e.g., *[music], ah, oh*) were ignored. After removing subtitle files that were not suitable for coding due to YouTube's automatic language detection assigning them with subtitles that were Chinese, Korean or Japanese ($n = 26$), and removing all text files that did not contain any mention of *Beats* or any corruption thereof ($n = 8$), 168 text files we included for concurrent time interval assessment. The timestamp (mm: ss) when the appropriate subtitle (*Beats* or equivalent) appeared in the video was used for further analyses. Because some participants missed an interval, or mentioned it twice in quick succession, all inter-Beats intervals less than 50 % of the true interval (<25 s) and higher than 150 % of the true interval (>75 s) were removed from the dataset. Across sessions, participants reported a median of 6 intervals, with mean interval durations ranging between 29 and 75 s ($M = 47.8$, $SD = 8.29$), indicating that participants were overall rather accurate in their assessment of 50-s intervals.

2.4.4. Emotional responses to gameplay

A 5-point Likert scale was used to measure participants' emotions: frustration, boredom, and enjoyment, immediately after playing each session of *Beat Saber*. We defined frustration as the feeling of being upset or annoyed as a result of being unable to change or achieve something (Britt & Janus, 1940). There were two items for frustration: 1) The session was frustrating; 2) The session was irritating. These items formed reliable measures for frustration across sessions: Easy condition: Cronbach's Alpha 0.76 ($M = 2.55$, $SD = 1.07$, $r = 0.61$, $p < .001$); Medium: Cronbach's Alpha 0.78 ($M = 2.20$, $SD = 0.79$, $r = 0.67$, $p < .001$); Hard: Cronbach's Alpha was 0.77 ($M = 3.71$, $SD = 0.98$, $r = 0.64$, $p < .001$). We defined boredom as a lack of interest, stimulation, or challenge (following Raffaelli et al., 2018). Boredom was also measured with two items: 1) The session was boring; 2) The session was uninteresting. These items formed borderline reliable measures for boredom across conditions: Easy: Cronbach's Alpha 0.66 ($M = 4.30$, $SD = 0.92$, $r = 0.49$, $p < .001$); Medium: Cronbach's Alpha 0.65 ($M = 2.12$, $SD = 0.61$, $r = 0.49$, $p < .001$); Hard: Cronbach's Alpha 0.80 ($M = 1.71$, $SD = 0.60$, $r = 0.66$, $p < .001$). Enjoyment was measured with three items: 1) The session was enjoyable; 2) The session was pleasant; 3) The session was satisfying. These items formed reliable measures for enjoyment across conditions: Easy: Cronbach's Alpha 0.88 ($M = 2.50$, $SD = 0.97$; Medium: Cronbach's Alpha 0.91 ($M = 3.78$, $SD = 0.85$); Hard: Cronbach's Alpha 0.85 ($M = 2.73$, $SD = 0.93$).

2.4.5. Physiological arousal

Baseline HR ($M = 95.47$, $SD = 15.67$) and Baseline HRV ($M = 54.39$, $SD = 12.44$) were measured using a *Polar H10* heart rate monitor during the tutorial (baseline) and during each session. Higher HR and lower HRV indicate increased physiological arousal. HR was measured during gameplay in the easy condition ($M = 100.87$, $SD = 18.50$), medium condition ($M = 105.11$, $SD = 17.65$), and hard condition ($M = 110.86$, $SD = 17.76$). Similarly, HRV was also measured during gameplay in the easy condition ($M = 50.73$, $SD = 11.37$), medium condition ($M = 45.84$, $SD = 13.78$), and hard condition ($M = 43.14$, $SD = 14.19$).

2.4.6. Performance

Game performance for each gameplay session was measured in two ways: (1) a numerical score that players received at the end of each session, based on the angle of each swing towards a block, the accuracy of each block strike, and the duration and number of hit-streaks, and (2) an overall ranking provided by the game based on their score. Score was used to measure differences within each session and was rounded to the nearest thousand for comprehension. The numerical score for the easy condition ranged from 2.93 (thousand) to 85.32 (thousand) ($M = 46.28$, $SD = 19.13$), the medium condition ranged from 66.74 to 775.84 ($M = 351.52$, $SD = 203.98$), and the hard condition ranged from 27.30 to 382.68 ($M = 128.70$, $SD = 53.69$). Since conditions contained different numbers of blocks and variations in block positions reflecting differences in challenge level, different maximum scores could be obtained in each condition. Scores were used to compare performances within each condition, whereas rank could also be used to compare performances between conditions. Beat Saber calculates a rank per gameplay session based on a player's score in relation to the maximum score that can be achieved. From the highest to the lowest, the in-game ranks were S (coded as 6), A (coded as 5), B (coded as 4), C (coded as 3), D (coded as 2), and E (coded as 1). Rank for the easy condition ranged from E to S ($M = 3.49$, $SD = 1.34$), rank for the medium condition ranged from E to A ($M = 2.39$, $SD = 1.23$), and no participants received a higher rank than E for the hard condition ($M = 1$, $SD = 0$).

2.5. Manipulation check

To determine whether the manipulation worked as intended, two questionnaire items were administered after each gameplay session: 1) the session was too challenging, and 2) the session was too easy, with 5-point Likert-scale answer options. Paired-sample t-tests indicated that the hard condition was indeed considered subjectively more challenging ($M = 4.47$, $SD = 0.74$) than the medium conditions ($M = 2.24$, $SD = 0.79$), $t\ (69) = -18.21$, $p < .001$, and the medium condition was considered subjectively more challenging than the easy condition ($M = 1.17$, $SD = 0.38$), $t\ (69) = -11.40$, $p < .001$. Paired-sample t-tests also indicated that the easy condition was considered subjectively easier ($M = 4.44$, $SD = 0.93$) than the medium condition ($M = 2.27$, $SD = 0.72$), $t\ (69) = 17.09$, $p < .001$. Similarly, the medium condition was considered easier than the hard condition ($M = 1.20$, $SD = 0.44$), $t\,(69) = 10.46$, $p < .001$. Thus, the experimental manipulation of challenge worked as intended as all sessions were appropriately considered (too) challenging or (too) easy.

2.6. Data analysis

SPSS version 29 was used for data analysis. Multiple repeated measures analyses of variance (ANOVAs) were conducted to assess the overall effects of challenge level (easy, medium, hard conditions) on flow experience, time perception, HR, HRV, performance, boredom, frustration, and enjoyment. Repeated measures ANOVA was advantageous in our experiment because it differentiates within-subject from between-subject variability, thereby enhancing statistical power. Within-subjects factors included game challenge level ($n = 3$), while gender ($n = 2$) served as the between-subjects factor. The assumption of sphericity was evaluated using Mauchly's test, and corrections were applied where necessary to adjust degrees of freedom and estimate effect sizes (i.e., Greenhouse-Geisser correction). If Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated, these results are reported specifically. *Post-hoc* analyses were conducted for multiple pairwise comparisons between challenge levels, using post hoc Bonferroni tests to correct the p-value ($p < .05$). Effect sizes, indicated by Partial eta-squared (ηp^2) values, were computed to assess the practical significance of the findings. Additionally, Pearson's bivariate correlations were conducted to test for linear relationships between variables within sessions, and various t-tests were performed to compare differences between men and women, or between specific conditions.

3. Results

3.1. Gender differences

For game performance, there was a significant difference between men ($M = 3.95$, $SD = 1.16$) and women ($M = 2.88$, $SD = 1.64$) in baseline ranking, $t\ (68) = 3.19$, $p = .002$, Cohen's $d = 1.40$, indicating that men ($n = 38$) performed significantly better than women ($n = 32$) during the baseline session. Performance (scores) in the easy session did not show a significant difference between men ($M = 44.99$, $SD = 17.85$) and women ($M = 47.80$, $SD = 20.74$), $t(68) = 0.61$, $p = .549$, Cohen's $d = -0.15$. However, in medium session, men ($M = 406.05$, $SD = 206.81$) achieved significantly higher scores than women ($M = 284.69$, $SD = 182.17$), $t(67) = 2.56$, $p = .012$, Cohen's $d = 0.62$. Similarly, in the hard session, men ($M = 144.07$, $SD = 59.36$) performed significantly better than women ($M = 109.87$, $SD = 39.01$), $t(67) = 2.76$, $p = .006$, Cohen's $d = 0.67$. No significant differences in enjoyment between men and women were found. However, differences in flow between men ($M = 3.96$, $SD = 0.46$) and women ($M = 3.71$, $SD = 0.48$) were found during the medium session, $t(67) = 2.14$, $p = .018$. Thus, men reported higher flow than women in the medium session and performed better than women in both medium and hard sessions. This may be related to the finding that men reported having more experience with VR gaming over the last few years ($M = 1.89$, $SD = 0.83$) than women reported having ($M = 1.56$, $SD = 0.67$), $t(68) = 1.82$, $p = .037$. Therefore, gender was included as a fixed between-subjects factor when examining differences between gaming sessions in all multiple repeated measures ANOVAs.

3.2. Game challenge and flow

Multiple repeated measures ANOVA indicated a significant effect of condition on flow ($F(2, 67) = 12.09$, $p < .001$, $\eta^2 = 0.27$), suggesting that challenge level of a gameplay session significantly influenced flow. The interaction between condition and gender was not significant, $F(2, 67) = 2.10$, $p = .131$, $\eta^2 = 0.06$, indicating no interaction effect. *Post-hoc* pairwise comparisons with a Bonferroni adjustment indicated significant differences in flow levels across the three conditions. Specifically, flow in the medium condition ($M = 3.85$, $SD = 0.48$) was significantly higher than in the easy condition ($M = 3.22$, $SD = 0.58$), $SE = 0.07$, $p < .001$. Similarly, flow in the hard condition ($M = 3.45$, $SD = 0.55$) was significantly higher compared to the easy condition, $SE = 0.09$, $p = .030$. Importantly, flow in medium condition was significantly higher than flow in the hard condition, $SE = 0.07$, $p < .001$. Thus, participants in the medium condition experienced the strongest sense of flow, confirming hypotheses 1a and 2a.

3.3. Frustration, boredom, and enjoyment

Multivariate analysis showed a significant effect of challenge on frustration, $F(2, 67) = 7.60$, $p < .001$, $\eta^2 = 0.19$. The interaction between condition and gender was not significant, $F(2, 67) = 0.10$, $p = .376$, $\eta^2 = 0.03$, indicating no significant gender differences in frustration across conditions. Frustration in the easy condition ($M = 2.55$, $SD = 1.07$) did not significantly differ from frustration in the medium condition ($M = 2.20$, $SD = 0.79$), $p = .074$. While frustration in the hard condition ($M = 3.71$, $SD = 0.98$) was significantly higher than frustration in the medium condition, $p < .001$, and easy condition, $p < .001$. These results support hypothesis 2b that frustration levels were higher in the hard condition compared to the medium and easy conditions.

For boredom, the assumption of sphericity was violated, $\chi^2(2) = 15.59$, $p < .001$. Therefore, Greenhouse-Geisser correction was applied to adjust the degrees of freedom for violations of sphericity ($\varepsilon = 0.83$). The effect of challenge on boredom was significant, $F(1.66, 112.62) = 34.82$, $p < .001$, partial $\eta^2 = 0.34$. Multivariate analysis also indicated a significant effect of condition on boredom, $F(2, 67) = 24.71$, $p < .001$, $\eta^2 = 0.42$, but the interaction between condition and gender was not significant, $F(2, 67) = 0.15$, $p = .858$, $\eta^2 = 0.01$. Boredom in the easy condition ($M = 4.30$, $SD = 0.92$) was significantly higher than boredom in medium condition ($M = 2.12$, $SD = 0.61$), $p < .001$, and hard condition ($M = 1.71$, $SD = 0.60$), $p < .001$. Additionally, boredom in the medium condition was significantly higher than in the hard condition, $p < .001$. These findings indicated that as the challenge of gameplay sessions increased, boredom significantly decreased. The results thereby support hypothesis 1b that boredom levels were higher in the easy compared to the medium and hard conditions.

It was hypothesized that the medium condition would lead to more enjoyment than the hard or easy condition. Multivariate analysis showed a significant effect of challenge level on enjoyment, $F(2, 67) = 14.27$, $p < .001$, $\eta^2 = 0.30$. The interaction between condition and gender was not significant, $F(2, 67) = 3.10$, $p = .051$, $\eta^2 = 0.09$. Enjoyment in the medium condition ($M = 3.78$, $SD = 0.85$) was significantly higher than enjoyment in both easy ($M = 2.50$, $SD = 0.97$), $p < .001$, and hard conditions ($M = 2.73$, $SD = 0.93$), $p < .001$. There was no significant difference between enjoyment in the easy and hard conditions, $p = .342$. These results confirm hypotheses 1c and 2c as the medium challenge session was deemed most enjoyable. The general differences in flow, anxiety, boredom, and enjoyment across easy, medium, and hard conditions are shown in Fig. 1.

3.4. Retrospective and concurrent time perception

One-sample *t*-tests indicated that retrospective session time estimates were significantly overestimated only for the easy condition ($M = 9.32$, $SD = 2.41$), compared to the actual duration (8min 28sec = 8.47), $t(69) = 2.85$, $p = .006$. The other conditions did not differ significantly in their time estimates from actual duration. Multivariate analysis showed that condition did not significantly influence session time estimates, $F(2, 64) = 0.320$, $p = .727$, partial $\eta^2 = 0.01$. The interaction between condition and gender was also not significant, $F(2, 64) = 0.039$, $p = .962$, partial $\eta^2 = 0.00$. Session time estimates (in minutes) for the easy condition ($M = 9.32$, $SD = 2.41$) were not significantly longer than session estimates for the medium condition ($M = 8.90$, $SD = 1.99$), $p = .424$. Similarly, session time estimates for the hard condition ($M = 8.64$, $SD = 2.40$) were not significantly shorter than the medium condition, $p = .100$, nor were they shorter than the easy condition, $p = .106$. Thus, apart from an overestimation of duration in the easy (boring) condition compared to the actual time, no retrospective altered time perception was identified when comparing duration estimates across conditions.

Multivariate analysis showed that challenge level significantly influenced concurrent interval time estimates, $F(2, 64) = 4.283$, $p = .018$, partial $\eta^2 = 0.12$. The interaction between condition and gender was not significant, $F(2, 64) = 1.411$, $p = .252$, partial $\eta^2 = 0.04$. The 50-s time interval estimates for the medium condition ($M = 44.77$, $SD = 1.39$) were significantly shorter than both time interval estimates for the easy condition ($M = 49.75$, $SD = 1.80$), $p = .010$, and time interval estimates for the hard condition ($M = 48.26$, $SD = 1.44$), $p = .050$. There was no difference in interval estimates between easy and hard conditions ($p = .397$). One-sample *t*-tests indicated that concurrent interval estimates were significantly underestimated only for the medium condition ($M = 44.77$, $SD = 1.39$), compared to the actual 50-s requested interval time, $t(66) = -5.13$, $p < .001$. These results show that although players' retrospective session time estimates did not differ significantly,

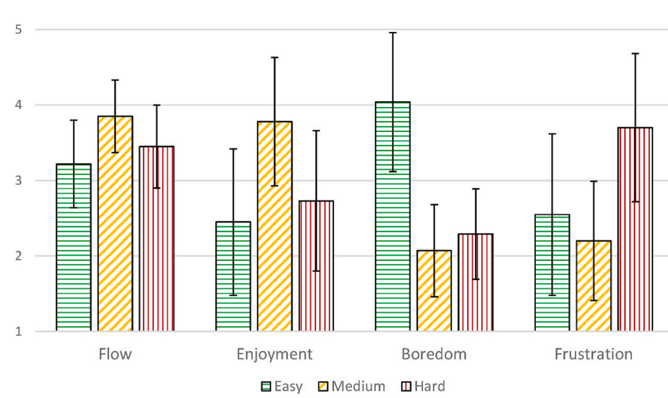

Fig. 1. Differences in flow, enjoyment, boredom, and frustration across three challenge sessions. *Note*: Bars show mean responses to statements on 5-point Likert-type scales and SDs.

concurrent time estimates of 50-s intervals showed shorter time interval estimates in the medium condition compared to both hard and easy conditions, and when compared to the actual interval time. Thus, an accelerated perception of time in the medium condition is partially confirmed (H1d and H2d). The results of retrospective and concurrent time perception are displayed in Figs. 2 and 3.

3.5. Physiological arousal

Multivariate analysis showed that, compared to HR baseline ($M = 95.47$, $SD = 15.67$), HR increased in the easy condition ($M = 100.87$, $SD = 18.50$), $p = .018$, HR further increased in the medium condition ($M = 105.11$, $SD = 17.65$), $p < .001$, and increased even further in the hard condition ($M = 110.86$, $SD = 17.76$), $p < .001$. Additionally, compared to HRV baseline ($M = 54.39$, $SD = 12.44$), HRV was lower in all three test conditions. HRV decreased in the easy condition ($M = 50.73$, $SD = 11.37$), $p = .039$, decreased further in the medium condition ($M = 45.84$, $SD = 13.78$), $p < .001$, and HRV decreased even further in hard condition ($M = 43.14$, $SD = 14.19$), $p < .001$. Taking the HR and HRV findings together, physiological arousal increased (higher HR and lower HRV) as challenge level of gameplay sessions increased (H1e), rather than reflecting an unambiguous flow state. The HR and HRV results across challenge sessions are displayed in Fig. 4.

3.6. Performance and flow

A Multiple repeated measures ANOVA was conducted to test whether flow leads to better performance with higher rankings between sessions. Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated, χ^2 (2) $= 6.36$, $p = .042$. Therefore, a Greenhouse Geisser correction was applied to adjust the degrees of freedom for violations of sphericity ($\varepsilon = 0.92$). Subsequently there was a significant effect of challenge level on game ranking, $F\,(2, 66) = 21.09$, $p < .001$, $\eta^2 = 0.39$. The interaction between condition and gender was also significant, $F\,(2, 66) = 5.40$, $p = .007$, $\eta^2 = 0.14$, indicating that the influence of condition on performance (rank) differed across gender. Specifically, men scored higher rankings than women as challenge increased. *Post-hoc* pairwise comparisons with a Bonferroni adjustment showed that participants' rank in the easy condition ($M = 3.48$, $SD = 1.35$) was significantly higher than that in medium condition ($M = 2.39$, $SD = 1.24$), $p < .001$, and hard condition ($M = 1.00$, $SD = 0.00$), $p < .001$. Similarly, rank in the medium condition was significantly higher than rank in the hard condition, $p < .001$. Within sessions, Pearson's correlations showed that flow neither had a significant correlation with performance score in the easy condition ($r = 0.18$, $p = .129$), nor in the hard condition ($r = 0.04$, $p = .739$). However, flow showed a significant positive correlation with scores in the medium condition ($r = 0.37$, $p = .002$). Therefore, player performance was only partially related to flow and challenge. Player ranking in the medium condition was significantly higher than in the hard condition, but lower than rankings in the easy condition. More importantly, within the medium condition (in which flow was highest), flow was positively correlated with players' scores.

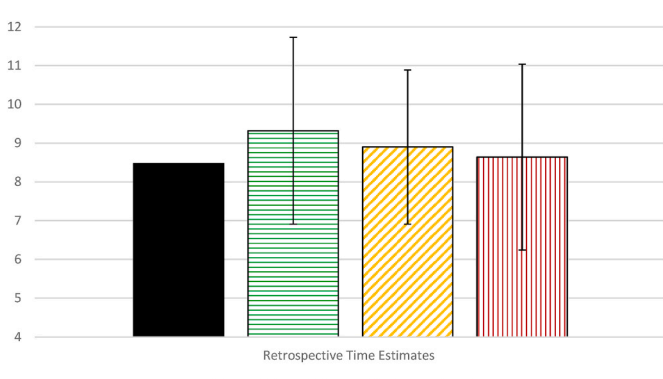

Fig. 2. Retrospective mean session time estimates (SD) in minutes across three challenge sessions. *Note*: Only significant difference was found between actual time and easy session, $p = .006$.

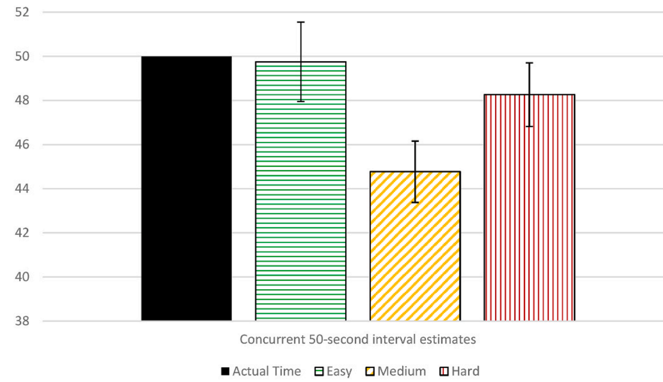

Fig. 3. Concurrent interval time estimates in seconds (SD) across three challenge sessions. *Note*: Medium condition interval estimates differed from all others, $ps < 0.05$.

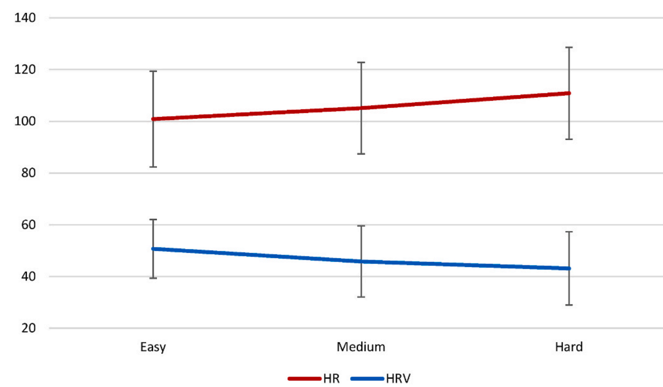

Fig. 4. Heart rate (HR) and heart rate variability (HRV) and SDs across three challenge sessions. *Note*: All session mean scores within HR and HRV differ significantly, $p < .001$.

4. Discussion

The objective of this study was to examine: (1) whether altered time perception, a key feature of flow, could be assessed behaviourally during a flow-inducing activity, and (2) to assess the relations between measures of time perception and traditional flow measures (self-reports and HR/HRV). Our approach to inducing flow using three game challenge levels (easy, medium, hard) was effective and showed both statistical and conceptual validity. The easy condition was indeed considered easiest by players, and the hard condition was considered hardest. Importantly, compared to the easy and hard conditions, participants showed most flow in the medium condition and found this condition less boring, less frustrating, and more enjoyable. Furthermore, those who experienced more flow in this session scored significantly more points. These findings are in line with previous research showing that flow occurs when there is a match between skill and challenges in Beat Saber (Lemmens & von Münchhausen, 2023) and that challenges that are perceived as too difficult can lead to frustration whereas challenges that are considered too easy can result in boredom (e.g., Fullagar et al., 2013).

Men generally performed better than women, with the exception of the easy condition, where no gender differences in performance were found. Additionally, men in the medium condition reported more flow than women did. Previous research has shown that gender differences in objective performance negatively affect game enjoyment of women disproportionately (Hopp & Fisher, 2017). Therefore, it seems plausible that a poorer performance (arising from an imbalance between skill and challenge) may have resulted in lower reported levels of flow among women. Generally, the finding that men performed slightly better overall, and thereby may have experienced more flow, is not uncommon in video game research, and has been discussed in greater detail in other publications (e.g., Bowman et al., 2013; Sherry, 2004).

In this study we employed a nine-item self-reported flow state questionnaire that reflects all nine dimensions of flow (Fang et al., 2013). Although this scale captured all nine dimensions commonly used in measures of flow (for a review, see Norsworthy et al., 2021), some researchers have argued that three of these dimensions (skill and challenge balance, clear goals, and immediate feedback) can also be understood as antecedents (or activity-related preconditions) to flow, whereas the remaining six dimensions are characteristics of this subjective state (Khoshnoud et al., 2020). Others have argued for a different dimensional structure of flow items, across two dimensions: "fluency," which is comprised of experiences related to fluent thought and action; and "absorption," which is based on sustained full attention (Lavoie et al., 2022), or across three dimensions: focus, motivation, and affect/emotion (Clark, 2023). Regardless of their dimensional allocation, several items of the flow scale (i.e., autotelic experience, clear goals, unambiguous feedback) were likely experienced very similarly across the easy, medium, and hard conditions of the Beat Saber game. This may have caused lower variance in scores on the flow scale between sessions, despite significantly different experiences in gameplay resulting from differences in perceived challenge. For example, during an easy gameplay session, the goals may have been as clear – and the feedback as immediate – as the medium session, yet the experiential items of flow were assessed completely different. This may also have affected the reliability of the flow scale, which was borderline reliable in some cases (see Method for specifics on reliability). Although differences in flow state still emerged, a scale based solely on experiential items (e.g., merging of action and awareness, focus and concentration, sense of control, loss of self-consciousness, and loss of time) would likely provide more internal validity for intra-game flow research in which the skill-challenge balance is manipulated.

5. Alternative indicators of flow

Despite previous evidence to suggest that HR and HRV are physiological indicators of flow (Bian et al., 2016; Keller et al., 2011; Peifer et al., 2014), our current findings do not clearly support the validity of these physiological correlates. Similar to Tozman et al. (2015), our results showed that HR increased and HRV decreased as the game became more challenging. Although our findings may suggest that moderate HR/HRV could be indicative of flow (compared to higher or lower HR/HRV in other sessions), it seems more plausible that the progressive increase in HR and decrease in HRV is related to the strenuous physical activity required to adequately hit the increasing number of blocks during progressively challenging gameplay sessions. Previous research has indeed shown that physical activity required for VR exergames, including Beat Saber, can induce greater HR variations (Charoensook et al., 2019). Furthermore, since flow was not positively correlated with HR nor HRV within any of the sessions, this physiological measure may not provide the best alternative to self-reported post-hoc flow questionnaires.

Players' time perception was measured in two ways: retrospectively (an estimate of the duration after each session) and concurrently (a time interval task during each session). The former is the traditional method, and the latter is novel. Regarding retrospective time perception, participants overestimated the duration they had played only in the easy condition (which was also rated as the most boring). Boredom is a mental state when a person increases their attention towards time, which leads to the perception of time passing more slowly and therefore an overestimation of its duration (Witowska et al., 2020). Although we expected that the flow-inducing (medium) condition would result in the strongest retrospective time underestimation, this time estimation was similar to that of the hard condition, and neither estimate was significantly shorter than the easy session overestimate. Previous research has shown similar findings related to the dissociation between passage of time and retrospective duration estimation (Droit-Volet & Wearden, 2016; Weiner et al., 2016), meaning that no relations between time assessment and flow were found. Furthermore, the similarity in retrospective estimates for medium and hard conditions may be attributed to a confounding effect of self-motion on time perception, as suggested by Rutrecht et al. (2021). A recent VR study showed that duration estimates increased with the velocity in which participants were moving through virtual space (Weber et al., 2020). In the hard condition, the perceived velocity increased as a function of the number of virtual blocks that moved towards the player. This effect of perceived velocity on time perception may have affected time estimates in the hard condition versus the other two conditions, causing session estimates to be similar to the flow-inducing medium condition.

Perhaps the most exciting finding in our study is that in the concurrent time perception task, participants perceived the flow-inducing (medium) condition as having significantly shorter intervals than both the easy and hard conditions. Participants estimated 50-s intervals to be approximately 10 % shorter in the medium gameplay condition, compared to the other conditions. Since the medium condition provided more flow, more enjoyment, less boredom, and less frustration, this supports our hypotheses, including the assumption that medium challenge leads to the perception of time 'flying by'. Our concurrent time task did not interrupt gameplay and had minimal cognitive demands, in that it required a simple verbal utterance that was done spontaneously by subjects in response to prior instructions, rather than via a visual cue within the gameplay (Cutting & Cairns, 2020). Given our results, it seems likely that these limited task requirements allowed participants to switch attention to stating the word 'beats', without breaking their flow state.

Concurrent interval tasks show promise for future flow research, but we acknowledge concurrent and retrospective time estimate methods both need improvement. Our retrospective estimate method asked participants to assess the duration of each session with a slider ranging from 5 to 15 min, with ten decimal points between minutes. Because all sessions actually had exactly the same length (8 min and 28 s, or 8.47 on the slider), the presented range may have caused slightly inflated time estimates due to the central tendency bias; participants relative propensity to choose the midpoint on scales (Akbari et al., 2024). Future research may account for this bias when presenting time assessment options. Our concurrent interval time measurement consisted of participants shouting the codeword "beats" every 50 s while playing. Due to the workload of manually coding 202 videos of 8.5 min each, we automated the subtitling using YouTube. However, we acknowledge that doing so introduced transcription errors as indicated by the list of homophones (e.g., *peace, bats, it's*), which may have led to some false positive and false negative counts. For future research we recommend using a longer response word, not recording the in-game music and sound, and starting each recording with some English phrases to correctly trigger the automated subtitle language detector. Despite its shortcomings, our method was successful at differentiating between the three conditions, detecting the smallest interval between "beats" in the flow-inducing medium condition.

To our knowledge, our concurrent interval time assessment measure is the first successful attempt to assess differences in time perception during video game play induced flow states.

The significant underestimation of time during a concurrent time interval task while in a state of flow shows that there is at least one useful diagnostic behavioural signature (Taylor et al., 2022) shown by humans in flow state. This may be useful in contexts where self-reported measures of flow are not practical; for example, in humans who cannot self-report and in non-human animals (Clark, 2023). Furthermore, concurrent time interval estimation is more temporally sensitive than the post-hoc estimate of overall time passage, and therefore offers an opportunity to detect at which point during an activity a person enters a flow state. Where our experimental design used three distinct game challenge levels, future research could use a digital game that more responsively adapts to player skill within one session, thus making it more likely and easier to detect if a person enters flow when they reach skill-challenge balance. The current findings are not only relevant for game-related flow research. Since great apes are able to perceive time passing, as shown by their performance in delayed gratification tasks (Beran & Evans, 2006), this study provides the first step towards a valid behavioural tool to assess whether flow is indeed a uniquely human experience.

CRediT authorship contribution statement

Jeroen S. Lemmens: Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Conceptualization. **Fay E. Clark:** Writing – review & editing, Conceptualization. **Xingjia Lyu:** Writing – original draft, Methodology, Investigation, Conceptualization. **Alex Taylor:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.
Time Flies When You're Having Flow (original data) (OSF)

References

Abuhamdeh, S. (2020). Investigating the "flow" experience: Key conceptual and operational issues. *Frontiers in Psychology, 11*, 158. https://doi.org/10.3389/fpsyg.2020.00158

Agarwal, R., & Karahanna, E. (2000). Time flies when you're having fun: Cognitive absorption and beliefs about information technology usage. *MIS Quarterly*, 665–694. https://doi.org/10.2307/3250951

Akbari, K., Eigruber, M., & Vetschera, R. (2024). Risk attitudes: The central tendency bias. *EURO. J. Decis. Process., 12*, Article 100042. https://doi.org/10.1016/j.ejdp.2023.100042

Beran, M. J., & Evans, T. A. (2006). Maintenance of delay of gratification by four chimpanzees (*Pan troglodytes*): The effects of delayed reward visibility, experimenter presence, and extended delay intervals. *Behavioural Processes, 73*(3), 315–324.

Bian, Y., Yang, C., Gao, F., Li, H., Zhou, S., Li, H., … Meng, X. (2016). A framework for physiological indicators of flow in VR games: Construction and preliminary evaluation. *Personal and Ubiquitous Computing, 20*, 821–832. https://doi.org/10.1007/s00779-016-0953-5

Bisson, N., & Grondin, S. (2013). Time estimates of internet surfing and video gaming. *Timing & Time Perception, 1*, 39–64. https://doi.org/10.1163/22134468–00002002

Brenner, P. S., & DeLamater, J. (2016). Lies, damned lies, and survey self-reports? Identity as a cause of measurement bias. *Social Psychology Quarterly, 79*(4), 333–354. https://doi.org/10.1177/0190272516628298

Britt, S. H., & Janus, S. Q. (1940). Criteria of frustration. *Psychological Review, 47*(5), 451.

Brown, R. M., Hall, L. R., Holtzer, R., Brown, S. L., & Brown, N. L. (1997). Gender and video game performance. *Sex Roles: Journal of Research, 36*(11–12), 793–812. https://doi.org/10.1023/A:1025631307585

Campbell, L. A., & Bryant, R. A. (2007). How time flies: A study of novice skydivers. *Behaviour Research and Therapy, 45*, 1389–1392. https://doi.org/10.1016/j.brat.2006.05.011

Charoensook, T., Barlow, M., & Lakshika, E. (2019). Heart rate and breathing variability for virtual reality game play. In *2019 IEEE 7th international conference on serious games and applications for health (SeGAH)* (pp. 1–7). IEEE. https://doi.org/10.1109/SeGAH.2019.8882434.

Chen, J. (2007). Flow in games (and everything else). *Communications of the ACM, 50*(4), 31–34.

Clark, F. E. (2023). In the zone: Towards a comparative study of flow state in primates. *Anima Behavior and Cognition, 10*(1), 62–88. https://doi.org/10.26451/abc.10.01.04.2023l

Cook, T., Roy, A. R., & Welker, K. M. (2019). Music as an emotion regulation strategy: An examination of genres of music and their roles in emotion regulation. *Psychology of Music, 47*(1), 144–154. https://doi.org/10.1177/0305735617734627

Cowley, B., Charles, D., Black, M., & Hickey, R. (2008). Toward an understanding of flow in video games. *Computer Entertainment, 6*(2), 1–27. https://doi.org/10.1145/1371216.137122

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience*. New York: Harper Perennial.

Csikszentmihalyi, M. (2000). *Beyond boredom and anxiety*. Jossey-bass.

Cutting, J., & Cairns, P. (2020). Investigating game attention using the distraction recognition paradigm. *Behaviour & Information Technology*, 1–21. https://doi.org/10.1080/0144929X.2020.1849402

Dietrich, A. (2004). Neurocognitive mechanisms underlying the experience of flow. *Consciousness and Cognition, 13*(4), 746–761. https://doi.org/10.1016/j.concog.2004.07.002

Dongas, R., & Grace, K. (2023). Designing to leverage presence in VR rhythm games. *Multimodal Technol. Interact., 7*(2), 18. https://doi.org/10.3390/mti7020018

Droit-Volet, S., & Wearden, J. (2016). Passage of time judgments are not duration judgments: Evidence from a study using experience sampling methodology. *Frontiers in Psychology, 7*, 176.

Engeser, S., & Rheinberg, F. (2008). Flow, performance and moderators of challenge-skill balance. *Motivation and Emotion, 32*, 158–172. https://doi.org/10.1007/s11031-008-91024

Fang, X., Zhang, J., & Chan, S. S. (2013). Development of an instrument for studying flow in computer game play. *Int. J. Hum. Comput. Interact., 29*(7), 456–470. https://doi.org/10.1080/10447318.2012.715991

Fong, C. J., Zaleski, D. J., & Leach, J. K. (2015). The challenge–skill balance and antecedents of flow: A meta-analytic investigation. *The Journal of Positive Psychology, 10*(5), 425–446.

Fullagar, C. J., Knight, P. A., & Sovern, H. S. (2013). Challenge/skill balance, flow, and performance anxiety. *Applied Psychology, 62*(2), 236–259. https://doi.org/10.1111/j.14640597.2012.00494.x

Hamari, J., & Koivisto, J. (2014). Measuring flow in gamification: Dispositional flow scale-2. *Computers in Human Behavior, 40*, 133–143.

Harmat, L., de Manzano, Ö., Theorell, T., Högman, L., Fischer, H., & Ullén, F. (2015). Physiological correlates of the flow experience during computer game playing. *International Journal of Psychophysiology, 97*(1). https://doi.org/10.1016/j.ijpsycho.2015.05.001, 1-7.

Hopp, T., & Fisher, J. (2017). Examination of the relationship between gender, performance, and enjoyment of a first-person shooter game. *Simulation & Gaming, 48*(3), 338–362. https://doi.org/10.1177/104687811769339

Huber, T., Mertes, S., Rangelova, S., Flutura, S., & André, E. (2021). Dynamic difficulty adjustment in virtual reality exergames through experience-driven procedural content generation. In *2021 IEEE symposium series on computational intelligence (SSCI)* (pp. 1–8). IEEE. https://doi.org/10.1109/SSCI50451.2021.9660086.

Ihamäki, P. (2014). GameFlow experience model: Understanding player enjoyment in pervasive adventure geocaching game. *International Journal of Wireless and Mobile Computing, 7*(6), 536–548. https://doi.org/10.1504/IJWMC.2014.065605

Im, S. H., & Varma, S. (2018). Distorted time perception during flow as revealed by an attention- demanding cognitive task. *Creativity Research Journal, 30*(3), 295–304. https://doi.org/10.1080/10400419.2018.1488346

Inal, Y., & Cagiltay, K. (2007). Flow experiences of children in an interactive social game environment. *British Journal of Educational Technology, 38*(3), 455–464.

Jackson, S. A., & Csikszentmihalyi, M. (1999). *Flow in sports*. Human Kinetics.

Jackson, S. A., & Marsh, H. W. (1996). Development and validation of a scale to measure optimal experience: The Flow State Scale. *Journal of Sport & Exercise Psychology, 18*(1), 17–35. https://doi.org/10.1123/jsep.18.1.17

Jin, S. A. A. (2012). "Toward integrative models of flow": Effects of performance, skill, challenge, playfulness, and presence on flow in video games. *Journal of Broadcasting & Electronic Media, 56*(2), 169–186.

Keller, J., & Bless, H. (2008). Flow and regulatory compatibility: An experimental approach to the flow model of intrinsic motivation. *Personality and Social Psychology Bulletin, 34*(2), 196–209.

Keller, J., Bless, H., Blomann, F., & Kleinböhl, D. (2011). Physiological aspects of flow experiences: Skills-demand-compatibility effects on heart rate variability and salivary cortisol. *Journal of Experimental Social Psychology, 47*(4), 849–852. https://doi.org/10.1016/j.jesp.2011.02.004

Khoshnoud, S, Alvarez Igarzábal, F, & Wittmann, M (2020). Peripheral-physiological and neural correlates of the flow experience while playing video games: a comprehensive review. *PeerJ, 8*, Article e10520. https://doi.org/10.7717/peerj.10520

Lavoie, R., Main, K., & Stuart-Edwards, A. (2022). Flow theory: Advancing the two-dimensional conceptualization. *Motivation and Emotion, 46*(1), 38–58. https://doi.org/10.1007/s11031-021-09911-4

Lee, M. C. (2009). Understanding the behavioural intention to play online games: An extension of the theory of planned behaviour. *Online Information Review, 33*(5), 849–872. https://doi.org/10.1108/14684520911001873

Lemmens, J. S., & von Münchhausen, C. F. (2023). Let the beat flow: How game difficulty in virtual reality affects flow. *Acta Psychologica, 232*, Article 103812. https://doi.org/10.1016/j.actpsy.2022.103812

Luthman, S., Bliesener, T., & Staude-Müller, F. (2009). The effect of computer gaming on subsequent time perception. *Cyberpsychology: Journal of Psychosocial Research on Cyberspace, 3*(1).

Nakamura, J., & Csikszentmihalyi, M. (2002). The concept of flow. *Handbook of positive psychology, 89*, 105.

Norsworthy, C., Jackson, B., & Dimmock, J. A. (2021). Advancing our understanding of psychological flow: A scoping review of conceptualizations, measurements, and applications. *Psychological Bulletin, 147*(8), 806.

Nuyens, F. M., Kuss, D. J., Lopez-Fernandez, O., & Griffiths, M. D. (2020). The potential interaction between time perception and gaming: A narrative review. *International Journal of Mental Health and Addiction, 18*, 1226–1246. https://doi.org/10.1007/s11469-01900121-1

Peifer, C., Schulz, A., Schächinger, H., Baumann, N., & Antoni, C. H. (2014). The relation of flow-experience and physiological arousal under stress—can u shape it? *Journal of Experimental Social Psychology, 53*, 62–69.

Raffaelli, Q., Mills, C., & Christoff, K. (2018). The knowns and unknowns of boredom: A review of the literature. *Experimental Brain Research, 236*, 2451–2462.

Rau, P. L. P., Peng, S. Y., & Yang, C. C. (2006). Time distortion for expert and novice online game players. *CyberPsychology and Behavior, 9*(4), 396–403.

Redelmeier, D. A., & Kahneman, D. (1996). Patients' memories of painful medical treatments: Real-time and retrospective evaluations of two minimally invasive procedures. *Pain, 66*(1), 3–8.

Rutrecht, H., Wittmann, M., Khoshnoud, S., & Igarzábal, F. A. (2021). Time speeds up during flow states: A study in virtual reality with the video game thumper. *Timing & Time Perception, 9*(4), 353–376.

Schmierbach, M., Chung, M. Y., Wu, M., & Kim, K. (2014). No one likes to lose. *Journal of Media Psychology, 26*(3), 105–110.

Sherry, J. L. (2004). Flow and media enjoyment. *Communication Theory, 14*(4), 328–347. https://doi.org/10.1111/j.1468-2885.2004.tb00318.x

Simen, P., & Matell, M. (2016). Why does time seem to fly when we're having fun? *Science, 354*(6317), 1231–1232. https://doi.org/10.1126/science.aal4021

Sweetser, P., & Wyeth, P. (2005). GameFlow: A model for evaluating player enjoyment in games. *Computer Entertainment, 3*(3), 3. https://doi.org/10.1145/1077246.1077253, 3.

Szpak, A., Michalski, S. C., & Loetscher, T. (2020). Exergaming with beat saber: An investigation of virtual reality aftereffects. *Journal of Medical Internet Research, 22*(10). https://doi.org/10.2196/19840

Taylor, A. H., Bastos, A. P., Brown, R. L., & Allen, C. (2022). The signature-testing approach to mapping biological and artificial intelligences. *Trends in Cognitive Sciences, 26*(9), 738–750.

Tian, Y., Bian, Y., Han, P., Wang, P., Gao, F., & Chen, Y. (2017). Physiological signal analysis for evaluating flow during playing of computer games of varying difficulty. *Frontiers in Psychology, 8*, 1121. https://doi.org/10.3389/fpsyg.2017.01121

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

Tordet, C., Erhel, S., Wodey, E., Jamet, E., Nardi, N., & Gonthier, C. (2021). The Flow Observational Grid: An observation-based solution to assess flow states. *Journal of Happiness Studies, 22*(7), 3069–3089.

Tozman, T., Magdas, E. S., MacDougall, H. G., & Vollmeyer, R. (2015). Understanding the psychophysiology of flow: A driving simulator experiment to investigate the relationship between flow and heart rate variability. *Computers in Human Behavior, 52*, 408–418. https://doi.org/10.1016/j.chb.2015.06.023

Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics, 66*(7), 1171–1189. https://doi.org/10.3758/BF03196844

Voiskounsky, A., & Wang, S. (2014). Flow experience while computer gaming: Empirical study. *Open Journal of Social Sciences, 2*(6), 1. https://doi.org/10.4236/jss.2014.28001

Weber, R., Huskey, R., & Craighead, B. (2017). Flow experiences and well-being. In L. Reinecke, & M. B. Oliver (Eds.), *The Routledge Handbook of Media Use and well-being: International Perspectives on theory and research on positive Media effects* (pp. 183–196). London: Routledge.

Weber, S., Weibel, D., & Mast, F. W. (2020). How self-motion in virtual reality affects the subjective perception of time. *Timing & Time Perception, 8*(2), 119–136.

Weiner, L., Wittmann, M., Bertschy, G., & Giersch, A. (2016). Dispositional mindfulness and subjective time in healthy individuals. *Frontiers in Psychology, 7*, 786.

Witowska, J., Schmidt, S., & Wittmann, M. (2020). What happens while waiting? How self-regulation affects boredom and subjective time during a real waiting situation. *Acta Psychologica, 205*, Article 103061.

Wood, R. T., Griffiths, M. D., & Parke, A. (2007). Experiences of time loss among videogame players: An empirical study. *CyberPsychology and Behavior, 10*(1), 38–44.

Yu, D., Wang, S., Song, F., Liu, Y., Zhang, S., Wang, Y., Xie, X., & Zhang, Z. (2023). Research on user experience of the video game difficulty based on flow theory and fNIRS. *Behaviour & Information Technology, 42*(6), 789–805. https://doi.org/10.1080/0144929X.2022.2043442