Rhythmic Stimuli Effects on Subjective Time Perception in Immersive Virtual Environments

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ABSTRACT

Time perception is an essential component of a user's experience and interaction in immersive virtual environments. This paper explores the performance and subjective time perception when carrying out a cognitive task in a virtual environment while being exposed to unrelated rhythmic stimuli. To this end, we devised an experiment comprising a simple object sorting task with varying rhythmic stimuli, investigating time experience in the form of time estimation and time judgment. The results imply varying effects depending on the usage of single stimuli compared to synchronized audio-visual effects. Single stimuli can lead to more pronounced time perception variations regardless of tempo, but these variations are not specifically compression or dilation. Synchronized stimuli, in turn, can lead to time compression or dilation, depending on the tempo. The results further imply that time being judged as fast or slow correlates to stimuli' tempo, while the presence of visual stimuli can negatively impact task performance. An active, purposeful rhythmic stimuli modulation to tailor individual time experiences can open up exciting opportunities in virtual environment design.

CCS CONCEPTS

• **Human-centered computing → Interaction techniques**; **Interaction design**; **HCI design and evaluation methods**.

KEYWORDS

Rhythmic stimuli, time perception, virtual environments

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1 INTRODUCTION

Time is an integral part of the human experience in real and virtual environments alike. Time perception is a subjective experience; therefore, it is interesting to investigate whether one can modulate that experience, and which factors affect time perception to what extent. The latter, in particular, has spawned many scientific studies this paper falls in line with. Specifically, we investigate relations between time perception and rhythmic stimuli in virtual environments. To isolate and study the effect of such stimuli on time experience, users in our experiment are asked to perform an unrelated cognitive task. Rhythm provides a simple way of synchronizing modalities and thus allows investigating the differences between single-modal and multi-modal, synchronized stimuli.

As part of the ChronoPilot project [1], which focuses on the active modulation of subjective time experience, a central objective of this study is to investigate whether rhythmic stimuli allow for influencing time experience in a cognitive task. Another objective is to investigate the interplay between synchronized stimuli modalities (auditory and visual). To this end, we investigate the following hypotheses:

- **H1** Performing a cognitive task, rhythmic visual (H1a) or auditory (H1b) stimuli affect time perception.
- **H2** The effect of rhythmic stimuli on time perception depends on the tempo of the rhythmic stimuli.
- **H3** Time distortions are more pronounced when using both stimuli types rather than individual types.
- **H4** Rhythmic stimuli affect task performance (H4a), varying depending on the tempo of the stimuli (H4b), which is amplified when using multiple stimuli (H4c).

Before focusing on the experiment, the data analysis, and the obtained results in Sections 3 and 4, the following section provides the necessary background by discussing related work. A discussion of the limitations, as well as a summary and outlook on challenges, opportunities, and research perspectives related to virtual environment design in Section 5 concludes the paper.

2 BACKGROUND AND RELATED WORK

Time perception encompasses different aspects such as time estimation, time judgment, and various representation models. In this paper, time perception is considered a personal interpretation of how time passed quantitatively (i.e., how much time one believes has passed) and qualitatively (i.e., how quickly that amount of time has passed).

The so-called clock model constitutes a classic and popular intrinsic model, which assumes the body or brain as a system dedicated to time perception [9]. The idea of an "internal clock" is often accompanied by a pacemaker-counter and oscillator model, suggesting that the brain has internal processes keeping track of time by producing "ticks" or "time units". The speed at which these time units are produced, the "clock speed", and whether some units are skipped can be influenced by external stimuli unrelated to time. In these models, attention or attentional resources can act as channels for the ticks

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produced to be accounted for by the processes [5, 6]. Studies employing these models generally consider two sources of subjective temporal distortions: arousal levels and attention. Arousal levels would affect the tick rate or the clock speed, resulting in a stretched perception of time, while attention acts as a gate or switch between the produced ticks and the accumulator: the less one pays attention to time (paying attention to something else), the more compressed is time [2, 3, 14].

Studies related to time perception distortions often overlap with the notion of flow, which is a psychological state of full attention on a task defined by Csikszentmihalyi with nine dimensions: challenge-skill balance, action-awareness merging, clear goals, unambiguous feedback, concentration on task, sense of control, loss of self-consciousness, time transformation, and autotelic experience [10]. However, flow is much more prominent in research than pure time perception. Since we aim to regulate subjective time perception actively and not only try to understand the underlying process, examining what affects flow is necessary. In their study comparing flow states in a session of the rhythm game Thumper between a VR and non-VR setup, Rutrecht et al. observed that both scenarios lead to a flow state regardless of the VR setup's higher immersion level. Interestingly, they also note that the passage of time and time estimation reported were not correlated [15].

Studying subjective time can be complex as various time judgment tasks involve different processing mechanisms, especially when comparing time estimations (i.e., asking a participant to give an estimation of an event in time units, such as seconds) and the feeling of time passage (i.e., asking if time passes quickly or not). For instance, it was observed that depressed subjects underestimate time but feel that time passes slowly [3] or that the boredom-prone performing a boring task feel a longer subjective time passage but no difference to non-boredom-prone when it comes to time evaluation [19]. A more positive example is that flow states induced by the video game Thumper lead to the faster passage of time but without time estimation errors [15]. Generally, time passage appears to be more tied to attention, while time duration estimation would be tied to memory [3, 22].

Following the overview of time perception notions and their different dimensions, the subsequent discussion focuses on research related to rhythmic stimuli and how they affect user experience. Droit-Volet et al. [4] highlight the effect of a musical piece's emotional valence and orchestration on time perception, identifying tempo as one of the core elements of a musical piece that can affect time perception. Indeed, tempo tends to affect arousal; hence faster tempi lead to time dilation. A recent study by Hammerschmidt et al. [7] explored different timing evaluations (reproduction, estimation, and subjective rating) of instrumental excerpts of Disco songs at different tempi reveals interesting properties about tempo related to time perception. Faster tempi yield longer duration reproductions, but no effects are observed for duration estimations. Depending on the measure, a tempo difference of at least 20 BPM is required for stretching the duration.

In the above studies, tempo is represented in the form or at least as part of audio stimuli, which makes perfect sense since tempo can be associated with music and rhythm and, for instance, Lukas et al. [13] suggest that the auditory channel dominates the visual sense for time-processing tasks. However, Wang et al. [18] reconsider this in a later study by using visual stimuli containing more temporal information than the usual laboratory stimuli in the form of Point-Light-Display (PLD) dance motions. Presented with asynchronous PLD motions and simple audio tempos, participants had to indicate what they thought was the most fitting tempo globally. Visual stimuli have a more significant influence, suggesting that either under the right conditions, visuals dominate audio when it comes to time perception, or the prioritized channels only depend on the quantity of information conveyed by the stimuli.

Wöllner and Hammerschmidt [21] recently investigated the effect of cognitive load, arousal, and musical meter on time experiences. They varied the cognitive load (tasks) and arousal levels of music while keeping the tempo constant, finding that: (1) time passage is quicker under higher cognitive load (represented with a concurrent math task), (2) performing a concurrent motor task (tapping along with the music) results in a shorter perceived duration, and (3) for the tapping task, tapping to larger structures (half notes instead of eighth notes) of the same music resulted in both shorter duration estimates and faster time passage.

Rhythmic stimuli have also been shown to influence gait if patients are instructed to walk in synchrony with the stimuli, which can help with Parkinson's disease [12]. For older, healthy adults, Wittwer et al. observe that music cues lead to higher gait velocity and cadence [20]. However, in the context of gait, not all rhythmic cues are equal. In the above study, if music would affect both velocity and cadence, metronome cues would only affect cadence. Another study on healthy adults by Leow et al. [12] observes how effects vary depending on the groove of the music and the beat-perception abilities of the participants. More generally, synchronizing with a tapping task to medium and high rhythmic complexity (but not too low complexity) appears to be able to induce the "fluency of performance" dimension of flow but without the "absorption by activity" dimension (which includes the time passing distortions) [16]. Synchronizing or not with music also seems to affect social sympathy, as observed by Stupacher et al. [17] with synchronized tapping to music leading to more sympathy and unsynchronized tapping resulting in less sympathy. Like in [20], there is again a difference between music and metronome cues, as synchronous tapping does not lead to any difference.

The prospective paradigm appears more practical for experiments where as much subjective participant data as possible is gathered since, contrary to a retrospective approach, it allows for repeating similar tasks with changing parameters where the repetition of stimuli and their predictability affect time perception. Across studies, various effects can occur, such as time-order errors (TOEs) when judging stimuli depending on the presentation order. For instance, Harrison et al. [8] found that TOEs are greater when a stimulus involves a saccade while there is no effect of overlapping stimuli regarding time perception. Aside from TOEs, Makwana and Srinivasan [14] inquired what color participants wanted to see before showing the stimuli they needed for time estimation and observed that intention and predictability affect time perception. Moreover, Kruijne et al. [11] observe a repetition effect on the magnitude of sensory response due to neural repetition suppression, which leads to effects on time perception that are unrelated to changes in arousal or surprise. These notions highlight a potential challenge and source of bias regarding studies on time perception, as repeated scenarios and participants' preferences can affect time perception in a way that is out of our control.

3 EXPERIMENT

For our experiment, we recruited 50 participants through the online crowdsourcing platform Prolific with a balanced gender ratio, i.e., 50% male and 50% female, and no geographic restriction. The only technical requirement was that exclusively laptops and desktop computers were used, i.e., no mobile devices such as phones or tablets. The participants were provided with a link to a Unity WebGL build of the experimental app hosted on our servers. In a first step, we manually filtered out participants if their data was incomplete or if the data was incoherent and it was confirmed after inquiry that the participant incorrectly followed the instructions. Individual trials were then filtered from their output data if an asset did not load correctly or if the participant's computer was slowing down. Among the 39 retained participants, the female-male ratio was 51.3%-48.7%, with ages ranging from 18 to 65 (average 28.05 / median 24). Considering the retained trials, the female-male ratio is 51.7%-48.3% (age average 28.31 / median 24). The average number of trials retained per participant is 8.38 (median 9), corresponding to potential bootstrapping issues when loading the app data for the first trial. Table 1 indicates the total trials per stimulus mode.

	0	100	140	180	Total
None	38	-	-	-	38
AudioOnly	-	30	25	38	93
VisualsOnly	-	21	38	35	94
Both	-	31	35	36	102
Total	38	82	98	109	327

Table 1: Number of trials per stimulus mode

3.1 Trial Task and Design

The task during trials is to sort three-dimensional objects according to their shape (cube, capsule, or sphere). The objects are moved into two larger spheres acting as sinks that process only specific shapes indicated by a panel above; in the example shown in Figure 1, the left sphere accepts cubes or capsules, and the right sphere accepts capsules or spheres. New objects appear at the center of the virtual environment after the previous object is sorted away, i.e., disappearing with a small animation (cf. image sequence). The individual trials' duration is unknown to the participants; following a trial run, they were asked to complete a questionnaire asking for a time estimation in seconds, as well as an evaluation of how quick they felt the trial was and an evaluation of their fatigue, both on a Likert scale. Before the trials, we asked the participants to indicate their age and gender.

The conditions under which the participants are asked to perform the sorting task were defined by a combination of the following parameters:

- The **duration**, i.e., trial length (40, 50, or 60 seconds).
- The **tempo** of visual and auditory stimuli production (100, 140, or 180 beats per minute, or 0 for trials with no stimuli).
- Whether or not **visual stimuli** are produced, i.e., flashing pulses around the sortable object.
- Whether or not **audio stimuli** are produced. These resemble a metronome click sound.

All participants performed the task under 10 different random parameter combinations (excluding combinations of a 0 tempo value with any auditory or visual stimuli). The task order was also determined randomly for each participant.

3.2 Data

As indicated in Section 3.1, we collected demographic data such as age and gender per participant in a basic questionnaire prior to the experiment, i.e., outside of trials. In addition to the more detailed per-trial post-assessment questionnaire related to time estimation and fatigue, we recorded real-time data on (1) the evolution of correct and incorrect answers, as well as (2) the moments when visual or auditory stimuli were produced by the system, relative to both the audio file used as a basis for the effects and the start time of the trial. Recording the audio file time and the real-time trial time allows for correlating and filtering trials with either a bootstrap or slowdown issue; trials without audio would also use an audio file, but the sound was muted.

The next sections introduce and discuss the data extraction and processing in more detail.

3.2.1 Direct Variables and Functions. The following variables and functions can be directly extracted from the gathered data:

- $t \in T$: trial identifier t from all available trials T.
- $p \in P$: participant identifier p from all available participants P.
- $trials(p)$: all trial identifiers of a participant p.
- $participant(t)$: participant identifier of a trial t.
- $correct(t)$: number of correct sorts at the end of trial t.
- $trialLength(t)$: length of trial t in seconds.
- $reportedLength(t)$: reported length of trial t in seconds.
- $reportedFatigue(t)$: self-reported fatigue of a participant after performing trial t in an ordinal scale from 1 to 5.
- $reportedSpeedPerception(t)$: subjective participant rating of trial t's speed in an ordinal scale from 1 (slow) to 5 (fast).

3.2.2 Extracted Variables. To obtain a basis for comparison, the directly extracted participant data outlined is further normalized into the following variables:

- $correctPerSecondTrial(t)$: average number of correct answers per second during trial t.
$$\frac{correct(t)}{trialLength(t)}$$
- $correctPerSecondParticipant(p)$: average number of correct answers per second of a participant during trials.
$$\frac{\sum_{t' \in trials(participant(t))} correct(t')}{\sum_{t' \in trials(participant(t))} trialLength(t')}$$
- $correctNormalized(t)$: amount of correct answers per second of trial t normalized with 1, i.e., the average number of correct answers per second of a participant among all performed trials.
$$\frac{correctPerSecondTrial(t)}{correctPerSecondParticipant(p)}$$

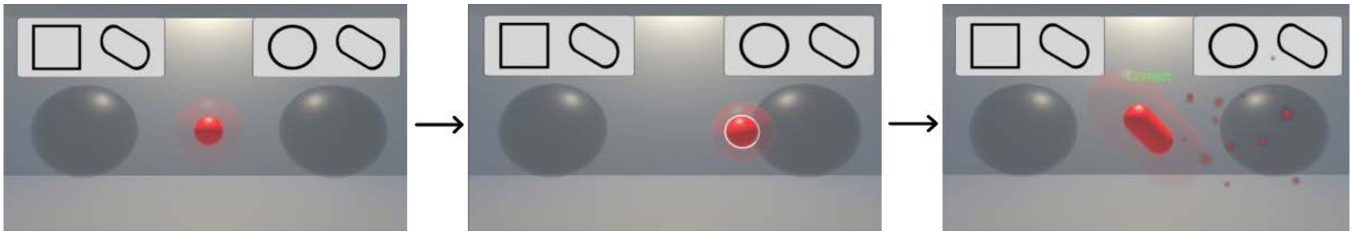

Figure 1: Example sequence of the experiment's sorting trial task, where users move geometric objects into matching sinks.

- $secondBias(p)$: ratio of the total of seconds of a participant p's trials and the total reported time, defining what the participant considers a second.

$$\frac{\sum_{t \in trials(p)} trialLength(t)}{\sum_{t \in trials(p)} reportedLength(t)}$$

- $deltaTimePerception(t)$: averaged delta per second between reported time (accounting participant bias) and trial length of a trial t.

$$\frac{secondBias(p) * reportedLength(t)}{trialLength(t)} - 1$$

- $abs(deltaTimePerception(t))$: absolute value of trial t's time perception delta.

3.2.3 Outcome Variables. The specific variables relevant to the analysis performed in this study are:

- $deltaTimePerception(t)$: if the difference between reported time and trial time shows too much individual bias, this variable represents a participant's variation in perception. A negative value indicates that the seconds of the trial t were reported as shorter than the other trial performed by this participant. A positive value means that the seconds were reported as longer.
- $abs(deltaTimePerception(t))$: instead of denoting how much longer or shorter a second is interpreted for a trial t compared to other trials performed by a participant, the absolute value represents the magnitude of the eventual time distortion.
- $correctNormalized(t)$: to simplify the analysis, we do not take into account negative answers to evaluate performance but only the amount of correct answers. A smaller number of correct answers would indirectly reflect the number of incorrect answers due to the time lost. Similar to a participant's variation in perception, this variable represents the variation in performance instead of the pure performance, with values < 1 indicating worse and > 1 better performances.
- $reportedSpeedPerception(t)$: the subjective interpretation of whether time drags or flies while doing a trial.
- $reportedFatigue(t)$: with relatively low trial numbers, reported fatigue should mostly depend on the participants, independent of trial parameters.

4 RESULTS AND DISCUSSION

As the primary goal of the experiment is to investigate the effect of rhythmic stimuli on time perception and task performance, two dimensions are considered for the stimuli: tempo (100bpm, 140bpm, 180bpm, or 0 for no stimulus) and type (visual pulse, audio kick, no stimulus, or both). Employing analysis of variance (ANOVA), an initial series of base ANOVAs is performed between the two dimensions and the outcome variables (Table 2). Additionally, stimuli ANOVAs between outcome variables and tempo for trials under each stimulus type further help investigate the effect of the tempo of that specific stimulus type (Table 3).

	Type		**Tempo**	
	F	*p*	*F*	*p*
deltaTimePerception(t)	1.33	0.26	1.35	0.26
abs(deltaTimePerception(t))	2.80	0.04	2.06	0.11
correctNormalized(t)	2.99	0.03	1.30	0.27
reportedSpeedPerception(t)	0.72	0.54	7.21	0.0001
reportedFatigue(t)	0.81	0.489	0.92	0.433

Table 2: ANOVAs on stimuli types and tempos.

	Audio		**Visual**		**Both**	
	F	*p*	*F*	*p*	*F*	*p*
deltaTimePerception(t)	0.27	0.76	0.67	0.51	2.86	0.06
abs(deltaTimePerception(t))	0.26	0.77	2.18	0.12	0.63	0.54
correctNormalized(t)	0.57	0.57	0.20	0.82	0.51	0.60
reportedSpeedPerception(t)	1.76	0.18	4.20	0.02	5.98	0.004
reportedFatigue(t)	3.48	0.04	0.89	0.41	0.25	0.78

Table 3: ANOVAs under specific stimuli types for tempos.

The base ANOVAs involving $deltaTimePerception(t)$ show no significant differences; however, the ANOVA between stimulus type and $abs(deltaTimePerception(t))$ reveals significant differences ($p = 0.04$), i.e., while no influence of the stimulus type was observed on the direction of time estimation's variations, the stimulus type in the experiment influenced the magnitude of the variations, indicating a possible validation of H1. Table 4 comprises a deeper analysis of this ANOVA using Tukey's range test (Tukey HSD), showing that compared to the absence of stimuli, each stimulus type leads to more substantial distortions (according to the diff value), thus validating H1a and H1b for the time estimation dimension of time perception. However, this is a near-significant tendency ($p < 0.1$), and only for single stimuli, the diff value is also in disfavor of the "Both" stimuli type compared to the single ones. This indicates that the combination of stimulus modalities (auditory and visual) potentially reduces the magnitude of time estimation variations under the influence of rhythmic stimuli.

	diff	lwr	upr	p adj
Both-AudioOnly	-0.04	-0.11	0.03	0.48
None-AudioOnly	-0.10	-0.20	0.001	0.053
VisualsOnly-AudioOnly	-0.003	-0.08	0.07	0.99
None-Both	-0.06	-0.15	0.04	0.43
VisualsOnly-Both	0.04	-0.04	0.11	0.54
VisualsOnly-None	0.10	-0.003	0.19	0.063

Table 4: Tukey HSD of ANOVA between stimulus type and abs(deltaTimePerception(t)).

As the stimulus type affects the magnitude of the variation of the time estimations, the absence of significant results in tempo might be due to these differences in stimulus type, which is why we also performed ANOVAs between time estimation variables and tempo (see Table 3). Here, differences appear between tempos on time estimations, revealing a near-significant tendency ($p = 0.06$) with the simultaneous use of audio and visuals with the variable $deltaTimePerception(t)$ but not with its absolute value. This suggests that when under the influence of both stimulus types, the tempo can modulate the direction of the subjective time estimation errors/variations but not the magnitude.

Further analysis employing Tukey HSD (see Table 5) shows that the difference is a tendency only between 180bpm and 140bpm (diff=-0.14, p=0.06); a tempo of 100bpm might not be enough for the rhythmic property to affect time estimation while the diff value suggests that the highest bpm value (180bpm) was rated as faster than a lower value of 140bpm for time estimation. These observations validate H2 for the time estimation dimension of time perception but only under the specific condition of the multi-modal stimuli while invalidating it for the single-modal ones.

	diff	lwr	upr	p adj
140-100	-0.11	-0.04	0.25	0.20
180-100	-0.03	-0.18	0.12	0.88
180-140	-0.14	-0.28	0.005	0.06

Table 5: Tukey HSD of ANOVA between tempo and correctNormalized(t).

The results regarding $abs(deltaTimePerception(t))$ indicate significant differences among stimulus types but not among tempos, while the opposite holds for the base ANOVAs involving $reportedSpeedPerception(t)$, thus invalidating H1 but validating H2 for the time passage aspect of time perception. From the analysis employing Tukey HSD (Table 6), the differences among tempos regarding $reportedSpeedPerception(t)$ are most significant between 180-100 (p=0.00005, diff=0.70), with tendencies for 180-0 (p=0.06, diff=0.50), 180-140 (p=0.102, diff=0.34) and 140-100 (p=0.102, diff=0.36). The different values among non-0 tempos (0 implying no stimuli and thus, no rhythm) suggest that higher tempos are rated faster than lower tempos. The stimuli ANOVAs suggest that this effect of tempo is significant for visual stimuli (p=0.02) and combined stimuli (p=0.004) but not necessarily for audio alone (p=0.18).

If the $correctNormalized(t)$ variable appears uncorrelated to tempo according to the base ANOVA, thus invalidating H4b, the significant p-value (p=0.03) between that variable and stimulus type

	diff	lwr	upr	p adj
100-0	-0.20	-0.73	0.33	0.77
140-0	0.16	-0.36	0.68	0.85
180-0	0.50	-0.02	1.01	0.06
140-100	0.36	-0.05	0.77	0.102
180-100	0.70	-0.30	1.10	0.00005
180-140	0.34	-0.04	0.71	0.102

Table 6: Tukey HSD of ANOVA between tempo and reportedSpeedPerception(t).

indicates the effect of stimuli type on performance. Further analysis (Table 7) indicates tendencies of visual-only stimuli to decrease performances compared to audio-only (diff=-0.03, p=0.097) and no stimuli (diff=-0.45, p=0.056), which validates H4a in the case of visual stimuli but not H4c as for the "Both" stimuli no significant differences are observed to other stimuli types.

A t-test between the $correctNormalized(t)$ variable and two classes considering either the presence or the absence of visual stimuli shows a significant decrease in performance in the group with visual stimuli (p=0.006, mean in group with visual stimuli is 0.997, mean in group without is 1.025).

Since, like for the $deltaTimePerception(t)$, there is an effect of the stimulus type on the performance, we also performed ANOVAs between $correctNormalized(t)$ and tempo for each type (Table 3) which did not reveal significant results.

	diff	lwr	upr	p adj
Both-AudioOnly	-0.02	-0.05	0.02	0.55
None-AudioOnly	0.01	-0.03	0.06	0.87
VisualsOnly-AudioOnly	-0.03	-0.06	0.004	0.097
None-Both	0.03	-0.014	0.08	0.28
VisualsOnly-Both	-0.014	-0.05	0.02	0.73
VisualsOnly-None	-0.045	-0.09	0.001	0.056

Table 7: Tukey HSD of ANOVA between stimulus type and correctNormalized(t).

The absence of stimuli or tempo effects on the reported fatigue is expected since fatigue depends on the participant's well-being prior to the experiment.

Correlations between the various outcome variables are shown in Table 8. $deltaTimePerception(t)$ and $reportedFatigue(t)$ being uncorrelated, while a correlation (p=0.001, rho=0.175) between $abs(deltaTimePerception(t))$ and $reportedFatigue(t)$ exists, indicates that fatigue does not influence the direction of the subjective time distortions but influences their magnitude. A tendency yet non-significant correlation (p=0.06, rho=0.104) is observable between $reportedSpeedPerception(t)$ and $correctNormalized(t)$, suggesting that the speed judgment is influenced by a participant's performance, even though scores were not shown during trials.

4.1 Limitations

One potential limitation of this study stems from the reported fatigue. As Table 3 indicates, the fatigue significantly varies among tempos under the audio stimuli, which might imply that the random

	[1]	[2]	[3]	[4]	[5]
[1] deltaTimePerception(t)	-	-	p=0.80	p=0.74	p=0.40
[2] abs(deltaTimePerception(t))	-	-	p=0.51	p=0.81	p=0.001 rho=0.175
[3] correctNormalized(t)	p=0.80	p=0.51	-	p=0.06, rho=0.104	p=0.341
[4] reportedSpeedPerception(t)	p=0.74	p=0.81	p=0.06, rho=0.104	-	p=0.16
[5] reportedFatigue(t)	p=0.40	p=0.001 rho=0.175	p=0.341	p=0.16	-

Table 8: Pearson correlation coefficients; Spearman if reportedSpeedPerception(t) or reportedFatigue(t) are involved.

assignment of the most tired participants happened to be to a specific tempo with tasks under audio stimuli. The Tukey HSD of this ANOVA shows that the difference is significant between 140bpm and 100bpm; thus, the results might be biased under these conditions. Due to the online nature of the study, we can assume that the hardware and displays used by the participants varied, which in turn might have caused a bias in the perception of the stimuli (e.g., hardware delay for display and audio, or screen solution). Even in the worst-case ANOVA scenario, we still have a post-hoc statistical power >0.95 for the statistically significant results (effect size 0.4, total sample size 102, 3 groups); however, there are some disparities among trials (cf. Table 1) per stimulus mode due to random trial assignment and data discarded due to bootstrap issues.

5 CONCLUSION

This paper discussed an experiment exploring the effect of rhythmic stimuli on a cognitive task's experience in a virtual environment regarding time perception and task performance. The results suggest that the different types of stimuli (audio, visual, or combined) have varying effects on time estimations. Single-type stimuli lead to higher variations, but combined stimuli can influence the direction of these variations depending on the tempo of the stimuli. However, no effect of tempo on time estimations is observed across all types of stimuli. When it comes to reported time passage being perceived as slow or fast, no general effect of stimulus type is observed, but an effect of tempo, which appears only in conjunction with visual stimuli. However, the same visual stimuli appear to distract enough to lower the task performance among the participants. A general limitation is the constraints and hardware variations due to the online nature of the study. As some results indicated only tendencies, further lab-based studies are necessary to confirm these implications. To this end, a follow-up study reproducing this experiment in VR while monitoring physiological signals to confirm these results and explore if the observed changes in time perception have direct physiological implications is currently in preparation. Another possible extension to the experimental setup is incorporating more complex stimuli dimensions beyond modality and tempo, which might affect time perception differently depending on the employed audio-visual stimuli and rhythmic patterns. Regarding time perception research, the study presented in this paper already highlights the potential of employing rhythmic stimuli to influence specific aspects such as time estimation variation and time judgment. More generally, such active and purposeful rhythmic stimuli modulation to tailor individual time experiences can create novel and exciting opportunities for designing immersive virtual environments.

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