The Effect of Auditory-Motor Synchronization in Exergames on the Example of the VR Rhythm Game BeatSaber

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Physical inactivity and an increasingly sedentary lifestyle constitute a significant public health concern. Exergames try to tackle this problem by combining exercising with motivational gameplay. Another approach in sports science is the use of auditory-motor synchronization, the entrainment of movements to the rhythm of music. There are already commercially successful games making use of the combination of both, such as the popular VR rhythm game BeatSaber. However, unlike traditional exercise settings often relying on periodic movements that can be easily entrained to a rhythmic pulse, exergames typically offer an additional cognitive challenge through their gameplay and might be based more on reaction or memorization. That poses the question as to what extent the effects of auditory-motor synchronization can be transferred to exergames, and if the synchronization of music and gameplay facilitates the playing experience. We conducted a user study ($N = 54$) to investigate the effects of different degrees of synchronization between music and gameplay using the VR rhythm game BeatSaber. Results show significant effects on performance, perceived workload, and player experience between the synchronized and non-synchronized conditions, but the results seem to be strongly mediated by the ability of the participants to consciously perceive the synchronization differences.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; Virtual reality.

Additional Key Words and Phrases: auditory-motor synchronization, rhythm games, exergames

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1 INTRODUCTION

While physical exercise is strongly related to physical and mental well-being [74], lack of physical activity and an increasingly sedentary lifestyle are major causes of most common chronic conditions such as obesity, type 2 diabetes, coronary heart disease, and depression [11] and thus constitute a major health issue. One problem that leads to physical inactivity is the lack of intrinsic motivation [76].

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One promising sports science approach to increase enjoyment and adherence to physical exercise as well as exercise performance is the use of music during exercise [89]. Especially the rhythmic properties of music seem to have a considerable effect, as the benefits can be particularly pronounced when the underlying rhythm of the music is aligned with the movements, an effect often referred to as *auditory-motor synchronization* [10, 89]. Furthermore, recent years have seen a rapid increase in the interest in and use of games for exercising, called *exertion games* or *exergames* [70, 71, 85]. An especially interesting technology for this field are Virtual Reality (VR) games, as they naturally enable direct physical interaction with the game environment, and the added immersion may have benefits for motivation.

Since music is deemed beneficial for exercising and has always been an important part of video games with significant psychological effects [30, 50, 56, 100], it seems only consequential to use music purposefully for the enhancement of exergame experiences as well. There already is a considerable market for rhythm games that rely heavily on auditory-motor synchronization, such as Dance Dance Revolution [51] or BeatSaber [8], the latter being one of the most popular VR games on the market and deemed suitable for physical exercise [49, 72].

In sports science, auditory-motor synchronization in the exercise context has mainly been investigated for exercises with periodic movements (like running, cycling, and rowing) [6, 10, 44, 89] where the entrainment of movement and steady beats appears relatively straightforward and there are usually no other elements that might divert the attention from the exercise. In exergames, there are typically gameplay elements involved that may guide the actions and movements of the player, produce cognitive overhead and distract from the actual exercise. Instead of periodic movements, the player may be required to perform more varied and less regular movements, based rather on reaction or memorization, as is the case in many rhythm games. Synchronized music might also be able to guide the player and let them anticipate the intended movements besides the usual visual stimuli.

While auditory-motor synchronization in a regular exercising context has shown the potential to be able to increase enjoyment and endurance as well as decrease heart rate [4, 6, 44, 58, 89], we could not find conclusive evidence if these effects can be transferred to exergames, especially when significant cognitive overhead is involved. To investigate this, we conducted a study in the VR rhythm game BeatSaber to measure the effect of different degrees of auditory-motor synchronization on physiological, psychological, and performance measures. With that we wanted to tackle the following research question: *To what extent does auditory-motor synchronization with music influence player experience, physiological measures, cognitive load as well as performance in the VR game BeatSaber?*

In the study, players played one level in the game under three different conditions:

(1) The rhythms of music and gameplay are synchronized with each other.
(2) The tempo of music and gameplay is the same, but the rhythms do not match.
(3) The tempo and rhythms of music and gameplay are completely decoupled from each other.

Gameplay-wise, the same level and tempo were used in each condition as well as the same piece of music, but the latter was temporally offset and its tempo manipulated to achieve the desired effects. The differences in heart rate, perceived workload, several player experience dimensions (perceived challenge, perceived mastery, and immersion), and performance metrics (score and hit rate of notes) were recorded. The results suggest that the effects heavily depend on the ability of the player to consciously perceive the degree of synchronization between music and gameplay. While we found significant effects on performance, perceived challenge, and several task load dimensions for those who recognized the synchronization differences between the conditions, there were almost no significant effects for those who did not. We discuss these findings and the resulting implications for future research concerning auditory-motor synchronization in games.

2 RELATED WORK

2.1 Rhythm and Synchronization

To investigate synchronization, we first have to clarify some fundamental concepts of rhythm. For this purpose, we will follow the definitions of Cooper and Meyer [21]. A *pulse* is "a series of regularly recurring, precisely equivalent stimuli" and marks off "equal units in the temporal continuum". The *meter* "is the measurement of the number of pulses between more or less regularly recurring accents", and pulses in a metric context are referred to as *beats*. The *tempo* of a rhythm is usually measured and defined as beats per minute (BPM). The arguably most common meter in Western music is the 4/4 meter that always groups four beats, with the first and the third one typically implied as *strong beats* (i.e., they are accented), while the second and fourth one are *weak beats*. For our sake, *rhythm* can be seen as the temporal structure of occurring events relative to the meter. In music, these events are typically acoustic stimuli (i.e., notes played by musical instruments and percussive sounds). In rhythm games, they are usually gameplay elements occurring at a fixed point in time that the player has to react to.

Based on that, two rhythms can stand in different rhythmical relationships to each other [54, 68]:

- *No synchronization:* The rhythms have different tempos.
- *Period-synchronization:* Both rhythms have the same tempo.
- *Phase-synchronization:* Both rhythms have the same tempo and the fundamental beats occur at the same time.

2.2 Music and Exercise

Research in sports science has been investigating the possible effects of music on exercising for a long time. A recent meta-analytic review by Terry et al. [89] of 139 studies suggests that listening to music before or during physical activity can be beneficial in various ways by increasing enjoyment, enhancing physical performance, reducing perceived exertion, and benefiting physiological efficiency, e.g., through increased oxygen efficiency. However, there are many variables at play that may mediate these effects, such as exercise intensity [43].

Significant effects have also been reported for different musical variables. Faster music has shown to increase endurance [3], performance in anaerobic exercise and sprints [35, 80], as well as work rate in recreational exercise [23, 25, 97]. Other studies found that "motivational" music (based on the model of Karageorghis et al. [46] of motivational qualities of music) increases endurance, but not perceived exertion [35, 42], while sedative music may lower heart rate and perceived exertion in endurance tasks [43]. Several more musical variables may have an effect but are still not understood well enough, such as self-selection, presence of lyrics, and musical complexity [43, 44, 89].

Demographic differences have been reported in the literature as well. Women were found to have a stronger preference to work out with music [78] and tend to have more positive feelings doing so [45]. According to literature, they also find it easier to synchronize their movements with music [45], and music tempo changes have a higher effect on their running cadence compared to men [96]. Older people prefer quieter and slower music during a workout [78] and are less likely to feel motivated by music [45].

The combination of music and video has been found to be even more beneficial than the individual video and music conditions by increasing work output [7, 59] and leading to higher exercise enjoyment [37]. Similar effects could be achieved with the combination of music and 360-degree video in VR that elicited more positive affective valence, greater perceived activation, and more dissociative thoughts than the individual conditions [9]. Besides listening to music during exercise, pre-task music listening has been found to influence grip strength [40] and may assist in preparing the body for high-intensity exercise [59, 98]. On the other hand, post-task music seems promising for faster regeneration after exercising by reducing heart rate, blood pressure, and perceived exertion [44] and facilitating heart rate variance [5].

However, one of the greater research gaps in this area of research is the lack of longitudinal studies on the subject, so the effects of using music on exercise adherence is still sparsely researched [19, 89].

2.3 Auditory-Motor Synchronization

The tendency to synchronize the own movement with music or other rhythmic auditory stimuli seems to be a fundamental human trait and occurs, to a limited extent, even in infants [99]. This process is a type of sensorimotor synchronization, the rhythmic coordination of movement and an external rhythm [81], often referred to as *auditory-motor synchronization* [10, 67].

Plenty of research has been done to investigate the human capabilities and limits concerning this synchronization process, for example with tapping studies where participants are usually instructed to tap with the finger to an auditory rhythm (often just a metronome) [81, 83]. Apart from these discrete, event-based timing tasks, other studies have focused on the synchronization of larger, periodic movements potentially involving the whole body with auditory rhythms [83]. Lower and upper sensorimotorical limits exist where at certain tempos people are not able to synchronize with a rhythmic stimulus anymore. The upper limit of auditory synchronization has proven to be much higher than for rhythmic visual stimuli (e.g., flashes of light) but is otherwise affected by several factors like rhythmic complexity or metrical accents of the external stimulus as well as the musical experience of the participants [82].

The degree of phase-synchronization also plays an important role. Usually, participants in such studies are instructed to entrain their movements exactly with the beat (in-phase), and there seems to exist a largely automatically occurring phase correction process [83]. However, participants usually have no problems synchronizing in-phase or anti-phase (exactly between beats), but in-between that only with high error rates [67]. When trying to synchronize with such phase differences, participants also tend to unintentionally entrain with the in-phase acoustic stimulus again on higher tempos, an effect called self-organization.

Several studies were concerned with gait synchronization to an external auditory rhythm. While some form of spontaneous entrainment could be observed in tapping studies [82], Mendonça et al. found that entrainment with rhythmic acoustic cues while walking usually does not occur spontaneously, but only when subjects are instructed to do so [65]. Moreover, it is easier for subjects to synchronize their gait with a metronome or music with a salient beat compared to music with a less salient beat, and "strong beat perceivers" generally have fewer problems synchronizing their gait [55]. Auditory-motor synchronization can also influence the walking speed of the gait by increasing stride length and vigor of movements [88]. In physical rehabilitation programs, rhythmic auditory stimulation (RAS), the use of music whose fundamental beat is acoustically accentuated, is utilized for gait training [69]. For example, gait training with RAS strategies has proven to facilitate improving gait parameters of Parkinson's disease patients [91], and to increase adherence to physical exercise of cardiac rehabilitation patients [2].

A typical form of auditory-motor synchronization that people frequently engage in is dancing. Several studies examined how different musical characteristics influence the evoked movements while dancing. While this is a complex phenomenon involving various movements with the whole body and occurring at different metrical levels [16], the temporal and spatial regularity of the dancing movements with the musical rhythm seems to be strongly connected to the pulse clarity and percussiveness of the music [15, 17]. Van Dyck et al. found that people moved more actively and synchronized their movements to the beat more accurately when the pressure of the kick drum (usually indicating the beat) was increased [95]. Furthermore, Karageorghis et al. showed that more complex and syncopated rhythms also lower the synchronization accuracy [41]. This suggests that strong rhythmic components and a clear, salient pulse seem to facilitate the auditory-motor synchronization process while dancing. Other studies also investigated the impact of various other variables on dance movements, such as personality and genre [61].

Auditory-motor synchronization seems also promising in an exercise context, but studies on this subject in sports science are still relatively scarce [89]. Most studies compare conditions with synchronized music to conditions without any music, leading to higher endurance, reduction of perceived exertion, increased heart rate, and higher states of pleasure [10, 42, 44, 47, 90], but that way it can not be clearly determined if these effects can be attributed to the synchronization effect or just the presence of music. However, individual studies comparing conditions with synchronized and non-synchronized music suggest that it can lead to higher endurance [4] and arousal [58] as well as lower heart rate [6, 52] and limb discomfort during cycling [58].

Several works have investigated auditory-motor synchronization strategies for running to stabilize running cadence, facilitate spontaneous synchronization and increase motivation [14, 27, 68, 96]. Auditory-motor synchronization is also an important part of the sonification of biofeedback, an area of research that increasingly raised interest in recent years [62]. Sonification systems making use of synchronization have been proposed for gait (re-)training [38, 39, 60] as well as exercising [63, 68].

2.4 Auditory Synchronization in Games

Research on the effects of synchronizing rhythmic auditory stimuli like music with gameplay or motions in the context of games is sparse. Levy et al. investigated the effect of the presence and tempo of background music in a cognitive multitasking game and noticed that the mouse movements significantly varied between silent and music conditions with the latter featuring more movements not directly related to gameplay or performance [56]. Participants stated that "the music beat made them want to work faster and time their motions with the music". These findings indicate that spontaneous entrainment of movements as little as controlling the mouse with the musical rhythm might even occur when there is significant cognitive overhead and no relationship between task and music.

Hufschmitt et al. examined the effects of different degrees of synchronization between music and gameplay in a variant of the well-known puzzle game Tetris on player performance [34]. They manipulated the music in a way that it was either always synchronized with the tempo of the (increasingly faster) falling tetriminoes, always a step behind or ahead, or behaved detrimentally to the gameplay by getting continuously slower. While player performance did not significantly differ between the conditions per se, the order in which the participants played under the different conditions seemed to have an effect.

Regarding exergames, music and its beneficial effects have been utilized in various works, for example, to teach dancing in physical education classes [31], to foster social interaction, physical activity and reminiscence in people suffering from dementia [92], and to incentivize higher physical exertion in high-intensity interval training (HIIT) by coupling the tempo of the music to the player's heart rate [48]. Soltani and Salesi [86] found that endurance was significantly higher in an exergame involving running on a treadmill when music was present compared to a no audio condition. In multiple studies investigating the use of exergames in school, students also particularly mentioned music as a motivating element [79, 87]. However, there is only a limited amount of literature focused on the impact of specific properties of music in the context of exergames, let alone auditory synchronization effects.

Finlayson et al. investigated the effect of "game-music synchronization" on performance, motivation, and enjoyment in their VR cycling exergame *Tour de Tune* [26]. An auditory-motor synchronization strategy was utilized in the game by coupling the target pedaling speed of the player (in revolutions per minute) to the tempo of the music (in beats per minute). However, the authors did not manipulate this synchronization method during their study, but the synchronization of the virtual cycling track to the intensity of the music instead (when the music got more intense, the track went uphill and thus the pedaling resistance increased, and vice versa). Two works used auditory-motor synchronization in VR exergames for high-intensity interval training (HIIT): Haller et al. found significant effects of rhythmic clapping by a virtual crowd on work rate and heart rate during cycling [32], Keesing et al. reported an increase of enjoyment and power output in a rowing game when the music was synchronized to the rowing movements (however, the sample size of the experiment was very small) [47].

The study of Lilla et al. is the only approach we could find where the effects of auditory-motor synchronization were examined in an exergame with reaction-based gameplay [57]. In their game designed for Parkinson's disease patients using motion tracking, players had to react quickly to game events (a mole popping up) and move accordingly (move their hand to the mole to feed them). In one condition, the beat of the underlying music was synchronized to the occurrence of the gameplay events, but no significant effect compared to non-synchronized music could be found with respect to player performance.

To the best of our knowledge, apart from this one study no work was done that examined and found potential effects of auditory-motor synchronization on (exer-)games with reaction-based gameplay, despite the on-going success of movement-based rhythm games like BeatSaber that utilize exactly this concept. The character of these types of games with often significant cognitive overhead as well as reactive full-body movements differs from most scenarios in related studies that typically feature repetitive and periodic movements. Still, there is no conclusive evidence which specific effects auditory-motor synchronization in such games might have on the player, especially with respect to the cognitive challenge, and to what extent.

3 METHOD

To investigate the effects of auditory-motor synchronization in reaction-based VR exergames on physiological and psychological variables as well as performance, we conducted a user study where participants were supposed to play such an exergame under different conditions with different synchronization strategies with respect to music and gameplay. We selected the VR rhythm game BeatSaber [8] for the experiment due to its popularity as a VR game, its strong coupling to music and rhythmic movement, its customization possibilities, and its potential to be used for exercising [49]. The game has been described as "a very viable option for a cardiovascular workout" and allows energy expenditure equivalent to that of playing tennis for more advanced players [72].

3.1 The Game BeatSaber

While the impact of auditory-motor synchronization in sports and exergames has been mostly investigated for kinds of exercise that rely on constant, periodic movements (like running, cycling and rowing), rhythm games typically require the player to react to visual cues with certain movements synchronized to the rhythmic properties of music, thus offering an additional cognitive challenge. In BeatSaber, the main objective is to slice through colored blocks (usually referred to as *notes*) coming towards the player with virtual light sabers using the motion controls of the VR controllers. The two sabers have different colors and the color of each note matches one of these colors, signaling that it has to be cut with the respective saber. Furthermore, each note has to be cut in a certain direction (upwards, downwards, sidewards, or in any diagonal direction) indicated by

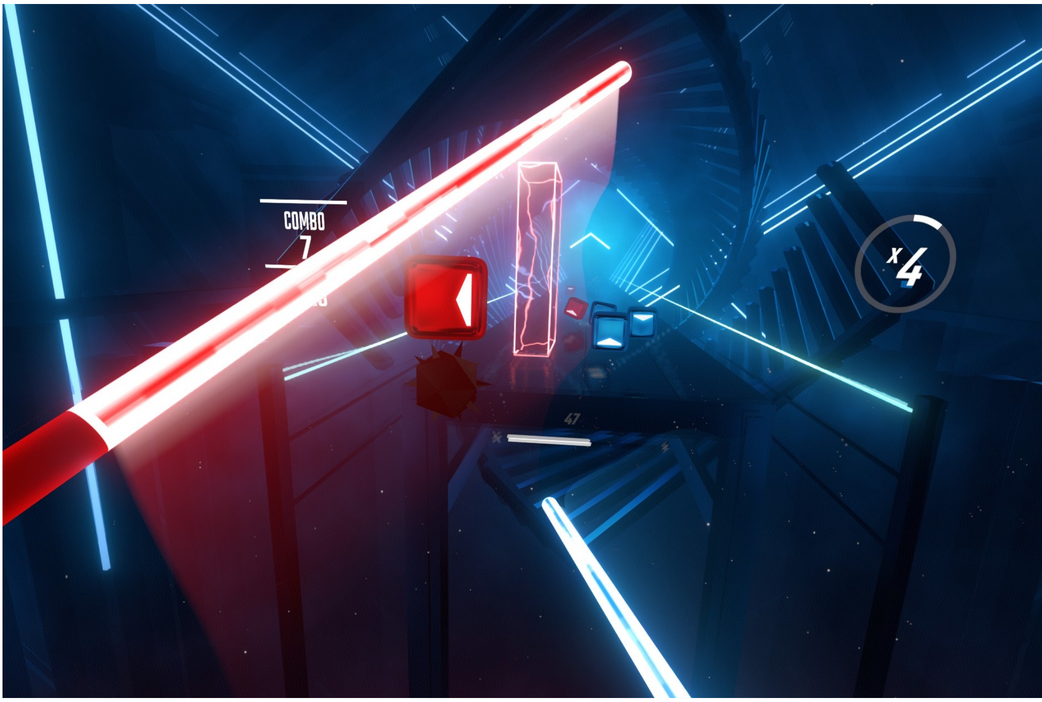


Fig. 1. A screenshot from the game BeatSaber [8] during a level. The two sabers and several gameplay elements (notes, a bomb, and a wall) can be seen.

an arrow pointing in that direction. Besides these blocks, there are also other gameplay elements: mines coming towards the player have to be avoided with the sabers and red walls have to be dodged by leaning or stepping to the side or crouching down. In more advanced difficulty settings, more layers of the music (such as beats, sounds, or the rhythm of the melody) are represented by matching game elements that have to be hit or avoided, leading to more complex gameplay patterns. That way the game requires the player to process a lot of information very quickly and react accordingly on higher difficulties, resulting in fast and sometimes complicated movements and offering a considerably high physical as well as cognitive challenge. A screenshot of the game mid-action with all relevant gameplay elements is shown in Figure 1.

A level in BeatSaber is tied to a specific piece of music and the gameplay patterns are usually designed to fit its rhythmic properties. The player gets points for hitting the notes correctly (i.e., with the correct hand and in the correct direction). The overall score as well as the number of correct cuts is then displayed to the player in the end. The score the player gets for hitting a note is dependent on two factors: the swinging angle of the movement when cutting the note and how close the cut is through its center. That means the game rewards big and precise swinging movements to cut the notes with a higher score, up to 115 per note (100 through the swinging angle, 15 through precision). Hitting many notes in a row correctly without missing one also increases a score multiplier that starts with the value 1, can get as high as 8, and is then multiplied with the points gained from each cut. However, the multiplier is reset to 1 when missing or incorrectly cutting a note, hitting a bomb with the sabers, or an obstacle with the head. Good timing, i.e., hitting a note perfectly on the beat has no impact on the score.

While BeatSaber already offers a variety of different levels in several difficulty levels out-of-the-box, it also allows for creating custom levels for any piece of music. For that, the respective track can be imported and the gameplay patterns can be created on a grid to fit the music. The temporal alignment of the grid is based on the number of beats per minute (BPM) that can be freely determined independently of the underlying piece of music. That means setting the BPM to a number that does not fit the music will result in gameplay that is decoupled from the underlying musical rhythm.

3.2 Experimental Conditions

Gameplay and music both have their own rhythmic properties that can be in different relationships to each other. The most obvious relationship (that is generally used in rhythm games) between the rhythms of music and gameplay is when they are aligned with each other. That is, both follow the same underlying tempo and the occurrence of the gameplay elements temporally matches the rhythm of the music. Thus, the movements of the player are supposed to be *synchronized* with the music. Music and gameplay are *non-synchronized* (or *decoupled*) when the underlying tempo of both does not match. However, this might have different effects on the player depending on the exact relationship of both tempos. While they may be able to ignore the music when they sense no relationship between it and the intended movements, the exact music tempo could still influence the experience as studies in different settings have found effects of music tempo on arousal [18], mental load [66], exercise intensity [25], gameplay and cognitive task performance [20, 34], and even perception of the own speed in a driving scenario [13]. So when decoupling a piece of music from the gameplay, the implications of speeding up or slowing down the music need to be considered. The magnitude of the tempo difference also plays a role, since players might perceive them as synchronized when the difference is small, but still feel that it is a bit off.

Another option is to keep the tempo the same for music and gameplay, but not match the gameplay elements to the musical rhythm. This can, for example, be achieved by shifting the rhythm of the gameplay (that is originally synchronized) by a constant offset in a way that it does not align with the intended beat anymore, i.e., the gameplay elements and resulting movements are preponed or delayed. This can be made in a musical or non-musical way: a musical offset would mean that the gameplay elements are shifted by a time period that still has a relation to the underlying meter, like a half beat (musically speaking an 1/8th note) or even a full beat (musically speaking onto the off-beat). With a non-musical offset, gameplay elements are shifted by a time period that has no recognizable rhythmical relationship to the music anymore. Offsetting the gameplay might confuse players and make it harder for them to precisely time their movements, but depending on the magnitude of the offset they might adapt to it or not even consciously notice it at all.

While the mentioned variants constitute only static relationships between music and gameplay, it could also change dynamically, for example by increasing or decreasing the tempo of the music over time, while the rhythm of the occurring gameplay elements stays the same. However, for the sake of this work, we will only consider the static cases.

Considering all that, we created a level in BeatSaber for the user study that is played in three different conditions. Each condition features the same gameplay in the same tempo and is accompanied by the same piece of music, but with varying degrees of synchronization:

- *Synchronized (S)*: Tempo and rhythm of music and gameplay are aligned.
- *Offset (O)*: Tempo of music and gameplay is the same as in *S*, but the music is shifted by a musical offset of three quarter notes, i.e., a gameplay element occurs three beats before the moment in the music it was intended to be aligned with.

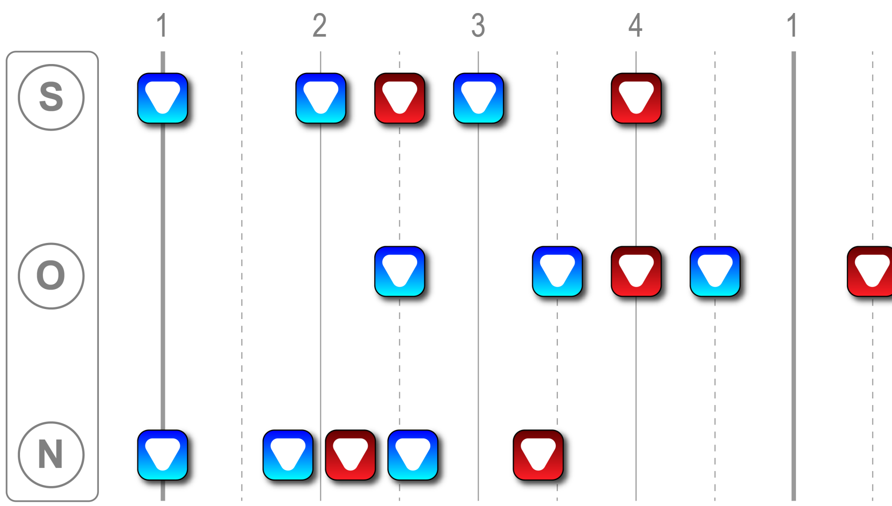


Fig. 2. Schematic visualization of the relationship between musical beat and gameplay objects in a 4/4 meter in all three conditions: *Synchronized (S)*, *Offset (O)*, and *Non-synchronized (N)*. The vertical lines symbolize full beats (quarter notes), the dashed lines half beats (eighth notes). The same general one-measure gameplay pattern is shown in all three conditions relative to the beat. In *S* and *O*, the notes align with the beat, but in the latter, they are temporally shifted by three half beats (in this example), so notes that were on the salient beats before are now off the beat and vice versa. In *N*, the tempo of the gameplay is faster than that of the music, so after the first note they do not align with the beat anymore.

- *Non-synchronized (N)*: Tempo of the gameplay is the same as in *S*, but the music is slowed down so they are decoupled from each other; the music is also offset so that there is no effect where the player thinks in the beginning they are aligned before diverging from each other.

A schematic depiction of the three principles can be seen in Figure 2.

In the *Non-synchronized* condition, we reduced the tempo by 5 BPM as that number proved as sufficient in pretests to give a sense of decoupling between gameplay and music. We decided on reducing the tempo instead of increasing it, because we hypothesized the lack of synchronization could diminish performance and increase mental load, and since faster music may also evoke this effect in general [20, 34, 66], this might compromise the results. For the *Offset* condition, we tested out different musical (one 1/4 note, three 1/4 notes, five 1/8th notes) and non-musical (0.5 seconds) offsets to determine a constellation where music and gameplay are disconnected without making them feel completely decoupled rhythm-wise as in *N*. Therefore we decided on the 3/4 offset since the 1/4 variant seemed too close to the original *Synchronized* condition while both other tested variants (that each shifted the gameplay elements in-between the beats) seemingly made it hard to relate the musical beat to the gameplay due to the relatively high tempo of the song and level, confusing some testers similarly to the *Non-synchronized* condition. So in this condition, the tempo of music and gameplay is synchronized, but not the rhythm and meter. For example, strong accents in the gameplay fall onto a weak beat or even into a break in the music and vice versa, constituting an interesting middle ground between the other conditions.

3.3 Design Considerations

The piece of music that was selected for the user study is *Angel Voices* by electronic music producer Porter Robinson (under the alias "Virtual Self"). The track is already available in BeatSaber with one of the standard levels, so it has already proven suitable for the game. It features a relatively high tempo of 166 BPM which might be beneficial for higher arousal during a workout [73] and proved as an appropriate tempo for the movements the player has to perform in BeatSaber. It was also chosen because of its musical and rhythmic variety: there are quiet and very intense parts, parts with a clear and steady underlying pulse, and such with more complex rhythms in melody and beat. However, the track was cut shorter so it only lasts around 3:45 minutes instead of the original 6:33 minutes which might have been too long and exhaustive.

A completely new level was designed with BeatSaber's off-the-shelf level editor synchronized to the selected piece of music. Several design decisions had to be taken into account for that. First of all, varying player skill and difficulty level have to be taken into account. We wanted to include players of varying difficulty levels, on the one hand to be able to generalize the findings, but also for practical reasons, since it is almost impossible to find a local sample with a similar skill level. Because of that, we decided to create two different difficulty levels, a "standard" and a "hard" difficulty, to cover the expected skill spectrum among participants as good as possible.

Initially, the harder variant of the level was designed, and after that gameplay elements in the faster and harder sections were removed or simplified to create the more accessible, easier version. Multiple iterations of the design were tested in pretests with members of the lab as well as external testers, all with different skill levels. The resulting feedback and observations were used to fine-tune the difficulty until the "standard" difficulty did not overwhelm novice players (after a warm-up phase with the game) and the "hard" difficulty proved still challenging enough for more experienced players who had no problems with the easier variant. During this process, it became clear that a warm-up routine in BeatSaber for each participant is important, so that their skill level (and thus the appropriate difficulty of the custom level) can be assessed and novice players can learn the game and reach a level where they are not overwhelmed by the custom level. Usually, a player can also fail a level when they make too many mistakes, but for the experiment the "No Fail Mode" was activated to prevent that.

Gameplay objects move towards the player at a higher or lower speed depending on the settings in the level. While a higher speed forces the player to process the information and react more quickly, potentially leading to a substantially higher cognitive load, the game is much more lenient with respect to timing when hitting the notes at a lower speed. We decided on a middle ground where the speed of the gameplay elements is relatively high so it requires the player to be more precise, but the patterns are kept simpler to not overwhelm the player too quickly.

Most standard BeatSaber levels are designed with complicated gameplay/movement patterns that challenge the processing capabilities of the player, on higher difficulties they are meant to be practiced for a while or even completely memorized by the player to beat them. In our experiment, the focus is rather on different rhythmic patterns and workout while limiting the cognitive challenge to an extent. So when it gets faster in our custom level, the patterns remain usually pretty simple without much change of arrow directions on the notes. There are also many walls the player has to dodge to keep them moving. That way we aimed to achieve a good mixture of different rhythmic patterns: slower ones with big and more complicated movements, fast ones with little cognitive challenge, regular rhythms close to the underlying beat and more rhythmically complex, syncopated ones (i.e., rhythms where many notes do not fall on the beat, but in-between). The different sections should also not be repeated exactly the same to reduce the learnability and memorability over the three trials.

3.4 Hypotheses

Sensorimotor predictive models in the brain enable humans to synchronize their movements with external stimuli while requiring only limited cognitive resources [54]. Furthermore, humans can synchronize to auditory cues with less effort and at a significantly higher rate than visual stimuli [82]. On top of that, studies have shown that people move more defined and show better tempo entrainment with the music when synchronizing to a salient audible pulse [15, 17, 95]. Based on all that and on observations in our pretests where players seemed to be able to make use of the predictable rhythmic qualities of the music to anticipate movements and gameplay patterns in the *Synchronized* condition, we hypothesize that synchronizing themselves with the music aids the performance and diminishes cognitive overhead. In the *Non-synchronized* condition, however, not only are those auxiliary auditory information missing but the music might also distract the players and thus produce additional cognitive load even when they are able to disregard the rhythm. In consequence, some testers also felt the *Synchronized* condition felt easier than playing without synchronization and they were more concentrated on the game, so in terms of player experience we expect a higher sense of mastery, lower perceived challenge, and additionally higher immersion in the *Synchronized* condition.

Synchronizing the own movements with music has also been shown to increase enjoyment during physical exercise [47, 94]. Further research found that entrainment with the music leads to more vigorous movement responses [54] and higher work output in exercise settings [28]. Thus, we hypothesize that when the player is phase-synchronized with the music (as in the *Synchronized* and *Offset* condition) they move with more vigor and purpose, exerting themselves more and thus increasing their heart rate compared to the *Non-synchronized* condition.

Based on these considerations we formulate the following hypotheses:

- H_1: Perceived workload is lowest in S and highest in N.
- H_2: Player experience in terms of perceived challenge, feeling of mastery, and immersion is highest in S and lowest in N.
- H_3: Player performance is best in S and lowest in N.
- H_4: Heart rate in S and O is higher than in N.

4 USER STUDY

To test our hypotheses, we conducted a user study with 54 volunteers and a within-subjects design. During the experiment, each participant played the designed level under all three conditions (s. subsection 3.2) in pseudo-randomized sequence using a Latin square design. Heart rate (HR), performance data, perceived workload and several player experience dimensions for each of the three conditions were measured. Each session of the experiment took about 60 to 75 minutes.

4.1 Participants

54 participants (33 male, 21 female) aged from 20 to 41 (average age: 26.3 years), mostly students of the local university, volunteered to take part in the study. According to the International Physical Activity Questionnaire (IPAQ) [53], 30 participants displayed a high, 9 a moderate, and 15 a low level of physical activity. Only 8 participants stated that they never played video games before and 11 only rarely, while 16 played occasionally and 19 frequently. 23 participants had no prior experience with rhythm games. The majority had never (19 participants) or only rarely (26 participants) used a VR system, 6 participants stated they used one occasionally and 3 frequently. 31 participants had experience playing a musical instrument for an average of 9.65 years (σ = 7.59) and 20 practiced dance sports or had practiced it in the past for an average of 4.23 years (σ = 3.82). 15 participants were assessed as skilled enough in the game to play on “Hard” difficulty, while the remaining 39

played the custom levels on the “Standard” difficulty setting. Only 4 participants stated they were familiar with the piece of music that was playing during the custom levels.

4.2 Apparatus

The experiment took place in a lab at the local university, the VR play area had a size of approximately 6 m^2. The HTC Vive Pro [22] was used as VR system, BeatSaber was played over SteamVR [93] running on a computer. The heart rate of the participants was measured with a Polar H10 heart rate sensor [24] that was attached to a chest strap. The colors of the sabers and gameplay elements in the designed levels used BeatSaber’s standard color scheme of red and blue, but for colorblind participants several alternative color schemes were prepared that could be switched to. Attention was paid to the applicable local hygiene regulations due to the COVID-19 pandemic.

4.3 Procedure

At the beginning of the experiment, volunteers were informed about the purpose, procedure and risks of the experiment and signed an informed consent to participate. Then they put on the chest strap for heart rate measurement as well as the VR headset and were instructed how to navigate through BeatSaber’s menu. Participants got time to accommodate themselves to the environment and when they had never played the game before, they were led through the tutorial that teaches the basic mechanics of the game. After that, they performed a warm-up routine of several different standard levels of BeatSaber with rising difficulty, for players not familiar with it to learn and get used to the game and for the experimenter to assess the skill level of the player. For that, specific levels on a difficulty similar to the custom level were selected (for both difficulties respectively).

The experimenter supervised the warm-up sessions, and participants proceeded to the experiment when they were able to succeed in the easier one of these levels with at least a medium rank and without seeming to be overwhelmed; when they even succeeded in the more difficult one in the same way, they were deemed skillful enough to play the custom level on “hard” difficulty. Usually, these warm-up sessions took around 15-25 minutes and no participant had problems to pass these minimum skill requirements for the experiment after some time. Until the end of this phase, the sound of the game was turned off, so the participants did not get primed by the usual synchronization in the standard BeatSaber levels for the experiment.

When the participant was deemed ready, a short break was made where the participant was told about the further procedure of the experiment. The participant was not informed about the nature and differences of the three conditions, they were only told that they would play three different levels and should try to achieve the highest possible score. They proceeded to play the custom level under all three conditions (now with sound) at the same difficulty setting and made a break after each of them to fill in a questionnaire about the level on paper. The experimenter also documented the performance values of the participant. The next experimental condition started only when the participant had reached their resting heart rate again.

After the participants had played all three levels, the experimenter conducted a semi-structured interview with one fixed introductory question: “Regarding the three BeatSaber levels with music you just played, what kinds of differences or similarities did you perceive between them?” As required, the experimenter asked further questions to inquire more details about the perceived differences and similarities regarding gameplay, music and especially the relationship between the two to assess how aware they were of the varying degrees of synchronization between the conditions. In the end, the participants filled out a short demographic survey before they were thanked and dismissed.

4.4 Measures

As a physiological measure, the heart rate (HR) measures of the participants where recorded while they played the three levels. The Polar H10 heart rate sensor [24] already filtered the recorded data in a satisfying manner, so we saw no reason for further processing. The performance data of the participants was recorded in terms of their score and the number of correctly hit notes. Based on that and the overall number of notes in the level (depending on the difficulty), a hit rate was calculated. To measure mental load, the raw version of the NASA-TLX questionnaire in German [33, 75] with all dimensions (mental demand, physical demand, temporal demand, perceived performance, perceived effort and frustration level) was used. Answers for all dimensions were given on a scale from 0 to 20, with 0 usually representing “low” and 20 representing “high” values, with the exception of the perceived performance dimension where 0 represents “good” and 20 represents “bad” performance (note however that this is consistent with the other dimensions, since higher task load is associated with a worse perceived performance). For the player experience measures, we used the dimensions challenge, mastery, and immersion of the Player Experience Inventory [1], each with three items answered on a 7-point Likert scale from 1 to 7, with 1 labelled “strongly disagree” and 7 labelled “strongly agree”. There was an additional item asking for the general enjoyment of the level on the same 7-point Likert scale (“In general, I thought this level was enjoyable”).

5 RESULTS

5.1 Quantitative Results

The absolute results of the different outcome variables (hit rate, score, average heart rate, NASA-TLX and PXI dimensions as well as enjoyment) of the experiment in the different conditions *Synchronized* (*S*), *Non-synchronized* (*N*), and *Offset* (*O*) can be seen in Table 1. The overall NASA-TLX and PXI scores were calculated as the mean of all their subdimensions, respectively. We conducted a repeated measures ANOVA and post-hoc tests with Bonferroni correction for each of the outcome variables over all three conditions to test the hypotheses. Significant effects ($p < .05$) could be found for perceived challenge ($p = .012$), PXI ($p = .042$), enjoyment ($p < .001$), and overall NASA-TLX score ($p = .008$) as well as its subdimensions temporal demand ($p = .003$) and frustration ($p < .001$). According to the post-hoc tests there were significant differences between conditions *S* and *N* in perceived challenge ($p = .013$), PXI ($p = .025$), enjoyment ($p = .004$), NASA-TLX ($p = .005$), temporal demand ($p = .014$), and frustration ($p < .001$); a significant difference between *S* and *O* was found for temporal demand ($p = .005$), and between *N* and *O* for frustration ($p = .049$) and enjoyment ($p = .011$).

It remains to be said that a few data points of some participants are missing for various reasons. In three instances, not all performance data could be captured from one of the conditions since the respective participants left the high score screen at the end of the level too quickly to record it; unfortunately, it is not possible to retrieve this data afterwards. Moreover, the HR of three participants was not correctly captured in one of the conditions and one accidentally skipped one page of the questionnaires. In these cases, the respective variables in all three conditions were excluded from analysis, but not the other correct data of the participant.

5.2 Effects of the Perception of Synchronization

Based on the answers to the semi-structured interviews we could directly evaluate how many people consciously noted the differences in auditory-motor synchronization between the conditions. 27 participants (50%) correctly observed that condition *S* was synchronized and in condition *N* music and gameplay were not synchronized or at least something “was off”. Of the 27 participants

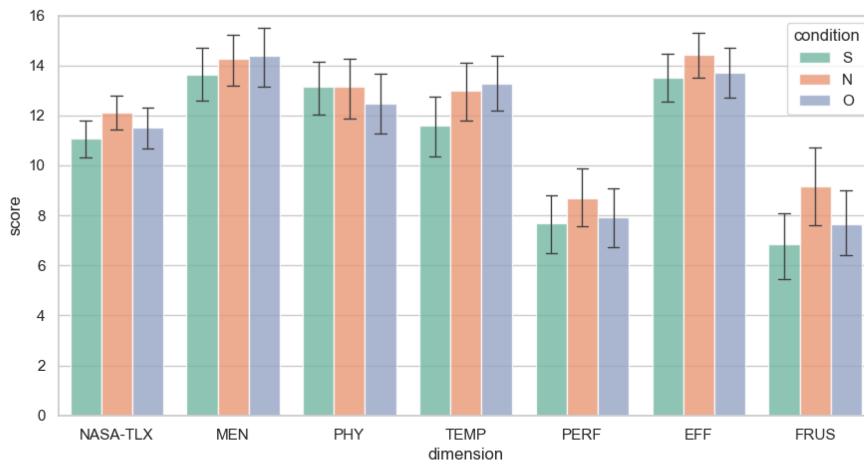


Fig. 3. Results of the NASA-TLX and its individual subdimensions for all three conditions. Means and 95% confidence intervals are shown.

	Sync.		***Non-sync.***		***Offset***	
	μ	σ	μ	σ	μ	σ
Hit rate	0.873	0.102	0.866	0.106	0.873	0.0873
Score	139083	104503	128887	91929	132348	91765
Avg. HR	131	25.2	130	23.4	130	22.8
NASA-TLX overall[2]	11.1	2.67	12.1	2.64	11.5	3.08
Mental demand	13.6	4.00	14.3	3.76	14.4	4.27
Physical demand	13.1	4.19	13.1	4.45	12.5	4.58
Temporal demand[2]	11.6	4.57	13.0	4.35	13.3	4.40
Performance	7.67	4.40	8.69	4.67	7.93	4.35
Effort	13.5	3.88	14.4	3.41	13.7	3.82
Frustration[3]	6.83	4.90	9.15	6.00	7.63	5.05
PXI overall[1]	5.56	0.770	5.31	0.959	5.49	0.837
Mastery	5.28	1.19	5.01	1.27	5.05	1.43
Challenge[1]	5.38	1.07	4.91	1.24	5.23	1.15
Immersion	6.03	0.995	5.99	1.05	6.20	0.846
Enjoyment[3]	6.26	0.705	5.61	1.55	6.15	0.960

Table 1. Mean values and standard deviations of all measured outcome variables.
$^{1}p < .05$, $^{2}p < .01$, $^{3}p < .001$

who did not perceive these synchronization differences correctly, 8 perceived something incorrectly (e.g., they perceived *N* as more synchronized than *S*), 14 stated that they felt the synchronization equally in all three conditions, and 5 did not consciously perceive any synchronization effects at all, mostly because they were focused too much on the gameplay to pay attention to it or they thought they noticed differences within but not between the levels. Furthermore, 18 participants (31.5%) perceived correctly that S was synchronized, but felt that O was a bit off, though only one explicitly noticed that it seemed offset compared to the *Synchronized* condition. Overall, S was perceived by 30 participants (72.22%) as the most synchronized condition (or one of the most synchronized ones), N by 16 (29.63%) and O by 21 (38.89%); note that several participants mentioned multiple conditions as being equally synchronized.

We observed a significant difference between two groups of participants while conducting the experiment: those who consciously recognized the differences in synchronization between the conditions (the "synchronization perceiver" group) and those who did not (the "non-perceiver" group). We conducted further analyses on both groups individually ($N = 27$ for each) by again using repeated measures ANOVAs and post-hoc tests with Bonferroni correction. In the group of participants who perceived the synchronization differences, we found statistically significant differences for hit rate, perceived challenge, PXI, enjoyment, overall NASA-TLX score as well as its subdimensions temporal demand, performance, effort (though none of the post-hoc tests were significant), and frustration. In the group of participants who did not perceive the synchronization differences, a statistical difference could only be found for mental demand but without any significance in post-hoc tests. More details can be seen in Table 2.

There were several conspicuous demographic differences between the two groups. Among the synchronization perceivers, substantially more participants stated that they play video games frequently (12, versus 7 in the non-perceiver group) and rhythm games as well (10, versus 2), while less had never played rhythm games before (8, versus 15). Participants in the synchronization perceiver group had also more experience playing instruments on average (7.96 years, versus 3.11 years in the non-perceiver group), but dancing experience did not seem to play a role (1.3 years practicing dance sports on average, versus 1.83 years in the non-perceiver group). Because the affiliation to one of these groups only became apparent at the end of the experiment, it was not possible to balance the groups with respect to order of conditions, so the results have to be treated with caution.

Based on these results we can evaluate our hypothesis as follows:

Considering H_1 ("Perceived workload is lowest in S and highest in N"), we found that there was a significant effect on the NASA-TLX score and several of its subdimensions. Especially in the synchronization perceiver group the general workload was reported lower in the *Synchronized* condition compared to the *Non-synchronized* condition, as can be seen in Figure 4a. Thus, we can accept H_1.

Contrary to H_2 ("Player experience in terms of perceived challenge, feeling of mastery and immersion is highest in S and lowest in N") we could find no effects on perceived mastery and immersion. However, there is a comparably strong significant effect ($\eta^2 = .092$ for synchronization perceivers) on perceived challenge in the synchronization perceiver group between the *Synchronized* and both other conditions. Furthermore, the strongest effect ($\eta^2 = .182$ for synchronization perceivers) among the investigated outcome variables was found on enjoyment between the *Non-synchronized* and both other conditions. Considering all this, H_2 can only be partially accepted.

Concerning H_3 ("Player performance is best in S and lowest in N"), a significant effect could only be found in the synchronization perceiver group, therefore it can also only be partially accepted. The differences between the performance scores (average hit rates) of the two groups can be seen in Figure 4c.

However, the only hypothesis we have to reject for both groups is H_4 ("Heart rate in S and O is higher than in N"), since no significant effects on heart rate could be found among participants.

	All				Perceived synch.				Not perceived synch.			
	F	*p*	η^2	*post-hoc*	*F*	*p*	η^2	*post-hoc*	*F*	*p*	η^2	*post-hoc*
Hit rate	0.41	.641	.001	/	4.86	.012	.025	*S/N*	1.29	.286	.007	/
NASA-TLX	5.12	.008	.023	*S/N*	6.95	.002	.056	*S/N*	0.57	.569	.006	/
Ment. dem.	1.95	.148	.008	/	2.21	.120	.018	/	3.26	.047	.028	None
Temp. dem.	6.34	.003	.028	*S/N*, *S/O*	7.57	.001	.049	*S/N*, *S/O*	0.81	.453	.010	/
Performance	1.26	.287	.009	/	3.24	.047	.043	*S/N*	1.08	.364	.018	/
Effort	1.66	.195	.011	/	3.20	.049	.027	None	0.09	.908	.002	/
Frustration	7.98	.001	.032	*S/N*, *N/O*	8.02	.001	.073	*S/N*	1.34	.272	.008	/
PXI	3.28	.042	.016	*S/N*	5.60	.006	.044	*S/N*	2.20	.121	.027	/
Challenge	4.65	.012	.028	*S/N*	11.3	.001	.092	*S/N*, *S/O*	1.06	.353	.018	/
Enjoyment	7.72	.001	.060	*S/N*, *S/O*	13.6	.001	.182	*S/N*, *N/O*	0.87	.426	.019	/

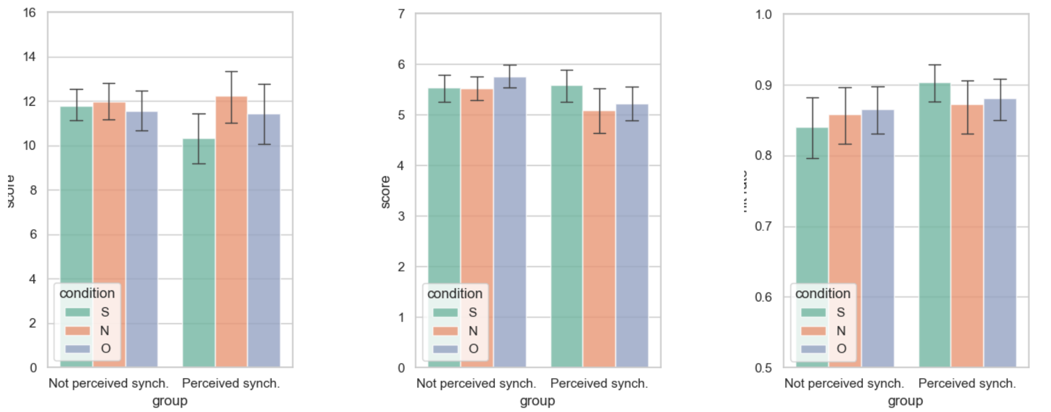
Table 2. Overview of the ANOVA results for all participants as well as the two individual groups of "synchronization perceivers" and "non-perceivers", including the effect size η^2. Only variables which were significantly affected in at least one of the groups are shown. The column *post-hoc* shows between which condition pairs the post-hoc tests found significance ($p < .05$).

5.3 Qualitative Feedback

To analyze the remaining qualitative feedback from the interview, we used inductive category formation roughly based on Mayring and Fenzl [64]. The goal was a summarization of the feedback by developing a category system of the responses. At the beginning, the units of analysis were determined as every complete statement of the participants given in the interview which were then paraphrased. Afterwards, these statements were grouped into categories by reduction and subsequently summarized, creating a category hierarchy. Finally, we checked the categorization of the initial statements with a back check. We identified the following major categories in the process: comments on the effects of the presence of music in general (as opposed to the warm-up phase without music), effects of synchronization between music and gameplay (or the lack thereof), differences in the perception of the music among conditions, and differences in the perception of the tempo of the gameplay among conditions.

Effects of the presence of music. With respect to the presence of music during play in comparison to the warm-up phase without sound prior to the experiment, participants mentioned the following effects: higher enjoyment (3 participants), higher motivation (1) and better performance (3). However, two participants reported negative effects as they felt "pressured" or "stressed", especially when the music got faster and more intense.

Effects of the synchronization between gameplay and music. Several participants commented on benefits when music and gameplay were synchronized, such as higher enjoyment (3 participants), engagement (3), and confidence (3) as well as better performance (10) at least under certain circumstances. Six of the latter mentioned that synchronization helped them guide their movements and anticipate the gameplay. One stated that it did not play a big role for them in the slower sections, but helped substantially when it got faster, another one felt it benefited the most during fast regular gameplay patterns. On the flip side, four participants specifically commented that when music and gameplay were perceived as *not* synchronized, the gameplay felt more demanding, because they had to concentrate more or gameplay elements "were not where they expected them". Notably, three participants stated they were able to blend out the music when it disturbed them and to



(a) NASA-TLX (b) PXI (c) Hit rate

Fig. 4. Comparative visualization of the results (means and 95% confidence intervals) for different outcome variables. The left group shows the results for the non-perceiver group in all three conditions, the right one for the synchronization perceiver group, respectively.

only concentrate on gameplay, and three others felt that the music in general did not affect their performance much, because they were focused on the game.

Differences in music perception. Three participants commented they perceived the music in the conditions differently, with one believing to have heard less percussive elements in *N*, one perceiving the music in *O* as a bit louder at the start (though the volume was always the same), and one thinking the piece of music in *S* might have been different from the other conditions.

Differences in tempo perception. Four participants felt that the tempo of music and gameplay in *N* was higher than in the other conditions, one perceived *S* as slower than the others. In *O*, three participants thought it was slower and two that it was faster than the others. Note that the tempo of the gameplay was infact the same in all conditions.

6 DISCUSSION

Our results suggest that the auditory-synchronization effects are strongly moderated by the participants' ability to consciously recognize the differences in synchronization among the conditions. Beforehand, we assumed that at least subtle effects would occur even for those who are not aware of the synchronization, but that does not seem to be the case for our experiment.

However, it remains an open question if the capability to actively sense the synchronization directly influences the respective outcome variables or if both are a consequence of the same underlying factors. Having experience in rhythm games or even knowing BeatSaber beforehand (without necessarily requiring to ever have played it) is likely to be connected with expectations of the synchronicity of the music to the gameplay, so these people are potentially more aware of it than those unfamiliar with the concept of rhythm games. People without gaming experience might also be more distracted and challenged by the underlying gameplay and not so adept in processing all the information quickly enough, and thus can not focus so much on the music. This is also supported by feedback from some participants of the non-perceiver group who stated to be preoccupied too much with the gameplay to pay attention to the music. The higher average experience playing musical instruments may contribute to a better sense of rhythm, while surprisingly dancing experience did not seem to play a role.

Researchers conducting experiments concerning music in various settings where the effects of rhythm and auditory synchronization might play a role should be aware that these effects may be moderated by the individual capability of the participants to correctly perceive and synchronize to the rhythm. This ability of beat perception is highly individual and may influence how well a person can synchronize their motions with music [55]. There have also been reported cases of "beat-deafness" when a person is not able to detect the beat of the music and move synchronized to it at all [77]. Therefore, it may be advisable in such experiments to determine the abilities of the participants in that regard, for example with the means of beat perception tests [29, 36] which have been explicitly developed for this purpose. Alternatively, since these tests may not always be feasible for experiments as they can be time-expensive, at least related demographic data should be collected such as experience in dancing and instrument playing as well as gaming and potentially VR experience in the context of games research. With this in mind, future research could also closer investigate the underlying factors that may predict the ability to perceive differences in auditory synchronization in games.

Our results show that at least the synchronization-perceiver group benefited from several significant effects in our study regarding mental load, player experience, and performance. With regards to the sub-dimensions of the NASA-TLX, the significantly higher perceived effort and worse perceived performance (note that high scores here mean a bad performance) among participants of the non-perceiver group fit the commonly expressed feedback that the synchronization facilitated their gameplay, and that they had to actively disregard the music and concentrate more on the gameplay to be successful. However, we would have expected that this also increases the mental demand of the participants, but surprisingly no significant effect could be found, just as for physical demand. The significantly lower temporal demand of the *Synchronized* condition compared to the other two might indicate that the game feels more hectic when music and gameplay do not align perfectly. Even in the non-perceiver group, several participants (wrongly) felt that they noticed differences in tempo between the levels, with the *Non-synchronized* or *Offset* condition typically perceived as the fastest. This effect might also occur because the music in both conditions can feel a bit "behind" the gameplay rhythm: in the *Non-synchronized* condition because it is 5 BPM slower, and in the *Offset* condition because it is shifted three beats to the back. It might be interesting to see if this changes when the relationships are reversed, i.e. the music is either faster or shifted forward. The strongest effect among the NASA-TLX subdimensions could be observed on frustration ($\eta^2 = .073$ for synchronization perceivers). Some participants of the synchronization perceiver group stated they felt uncomfortable when beat and gameplay did not align, in a few instances participants even clearly expressed their frustration after playing the *Non-synchronized* condition.

Though the conditions do not seem to have influenced perceived mastery and immersion, there is a comparably strong significant effect ($\eta^2 = .092$ for synchronization perceivers) on perceived challenge in the synchronization perceiver group between the *Synchronized* and both other conditions. This matches with the frequent positive feedback of participants about how synchronization facilitates their gameplay and helps them anticipate the movements. Furthermore, the strongest effect ($\eta^2 = .182$ for synchronization perceivers) among the investigated outcome variables was found on enjoyment between the *Non-synchronized* and both other conditions. This suggests that auditory-motor synchronization can increase enjoyment and lower frustration for at least some participants, which is especially interesting in the context of motivation in exergames.

The effects on player performance are not as pronounced as we would have expected, and only occurred in the synchronization perceiver group. Common feedback of participants of that group suggests that they indeed were able to anticipate the gameplay better in the *Synchronized* compared to the *Non-synchronized* condition based on the rhythmic cues given by the music. This could be explainable through the support of the predictive capacity of sensorimotor control mechanisms as reported in literature [54]. However, it also shows that this seems to be a relatively active process that only works when the player is aware of it (at least in the context of BeatSaber).

Furthermore, while for individual participants effects on heart rate could be observed across conditions, it varied strongly among participants. Some seemed to exhaust themselves more when the music was synchronized to their movements with one explicitly stating that in the interview. However, others (synchronization perceivers as well) exhibited higher heart rates in the *Non-synchronized* condition, possibly because they were stressed out more and had to make up for the perceived higher difficulty.

For the *Offset* condition, we had decided for an offset of three beats, leading to the gameplay often not exactly fitting the music but still being in-phase with it. Significant effects of this condition compared to the others have only been found for perceived challenge, enjoyment, and the NASA-TLX dimensions Temporal Demand and Frustration. We would expect that the effects are more pronounced when the gameplay is offset in a way that it is out-of-phase with the music, e.g. by the initially considered five eighth notes (so it would be anti-phase) or an unmusical offset of 0.5 seconds.

Up to now, it is unclear which role the use of VR plays with respect to the impact of auditory synchronization strategies. In general, the effects of audio dimensions in VR have been found to play a less prominent role compared to gaming on traditional monitor setups because players are more preoccupied with the sensory experience [84]. This could lead to a distraction from the music and moderate the synchronization effects, even in a game that is so centered around the music like BeatSaber. On top of that, the novelty effect VR typically exhibits in studies for participants without prior experience with the technology might influence results in a similar way. Future research should further address how VR influences auditory effects in general and the impact of auditory-motor synchronization in particular.

In general, future work needs to further explore under which circumstances auditory-motor synchronization can be used effectively in active games to benefit the player, since literature regarding this topic is still scarce. Two recent studies on VR exergames have especially found positive ergogenic effects, evoked through what seems more like spontaneous entrainment to music [47] or other auditory rhythmic stimuli [32] (though unfortunately, both are lacking validity because of small sample sizes). Both rather relied on continuous, periodic movement (rowing and cycling) to synchronize with the auditory stimuli. In contrast to this, our results suggest significant effects of auditory-motor synchronization can also occur in more reaction-based games potentially requiring significant cognitive and coordinative effort that may be reduced through synchronization effects. However, a similar study investigating the effects of auditory synchronization in a reaction-based exergame [57] could not find any effects. The study's target demographic was Parkinson's Disease patients with probably little experience with video games which may be a factor for the lack of synchronization effects (as discussed previously), especially since they were explicitly not instructed on how music and gameplay are connected (as in our study). But since the study did not raise any (documented) data regarding the participants' perception of the relationship between gameplay and music, the interpretation of the results and the reasons for the absent effect is limited. It seems that at least in this type of game subtle effects influencing the player sub-consciously through the degree of synchronization are limited. Instead, our results suggest that the synchronization of music and gameplay specifically aids players when they consciously perceive it and they can actively use the additional auditory information to anticipate the gameplay patterns and go with the music (as it was mentioned by several of the participants). In exergames, it may therefore be helpful to actively communicate to the player that the musical rhythm can guide them instead of relying on more subtle effects.

6.1 Limitations

There are a few limitations regarding generalizability to exergames in our study. First of all, our sample consisted mainly of students of the local university in their twenties, so it is not necessarily representative of the general population. The measured effects may vary especially for older generations with less experience with gaming and VR on average. Furthermore, BeatSaber can have a relatively high tolerance regarding timing to hit the notes and there are no scoring bonuses for timing the hit directly on the beat. This might limit the negative effects of non-synchronized music on performance and other variables compared to other games that focus more on precision in timing. For example, one participant who described themselves as a veteran in the rhythm game Dance Dance Revolution [51] thought that the effects would have been more pronounced there, because precise timing is crucial to its gameplay. As discussed before, it is also unclear if VR mediates the measured effects and if they apply to the same or similar extent to exergames that do not make use of this technology.

As we decided to employ two different difficulty levels to be able to offer players of various skill levels an appropriate challenge, the comparability between these two groups has to be taken into account as well when interpreting the results. 12 of the 15 players (80%) of the harder difficulty were able to correctly recognize the different degrees of synchronization across conditions. Accordingly, the measured effects between conditions were more pronounced compared to players of the standard difficulty. On average, they exhibited a lower mental load and higher hit rate than the other players which means they were subjectively slightly less challenged. Our method to categorize players to the appropriate difficulty level as objectively as possible by letting them play a "tie-breaker" level during warm-up is certainly still not foolproof. There were a few individual borderline cases where it is not guaranteed that results may be different had they been categorized for the respective other difficulty variant.

The scoring system in BeatSaber incorporates a number of specific factors to determine the player's score (cf. subsection 3.1) like combos and swing angles and thus is not necessarily a very expressive measure for our purposes. Because of the combo mechanic, little mistakes at the wrong moments are enough to strongly influence the score. It is also compromised by the fact that participants playing the hard version of our custom level were generally able to achieve higher scores because of the higher number of notes. For these reasons, the average hit rate is a more descriptive performance measure for our experiment's sake. Moreover, the permanent presence of the score during and the display of all performance measures after the level (including a rank given to the player based on their score) naturally affects the player's subjectively perceived competence and thus may also indirectly influence other outcome variables [12].

Since the players played the same level three times gameplay-wise to guarantee comparability between the conditions, learning effects have been pretty strong and may compromise the results despite counterbalancing. Effects among different synchronization conditions may vary based on the features of underlying gameplay patterns, e.g., if they are slow or fast, straight on the beat or syncopated and rhythmically complex. However, an individual examination of different gameplay patterns is hardly possible in BeatSaber as long as they are packed together in one level.

7 CONCLUSION

We conducted a study to examine the effects of different degrees of auditory-motor synchronization in reaction-based exergames on the example of the VR rhythm game BeatSaber. Results suggest that synchronizing the gameplay and thus the player's motions to the beat of the music may significantly increase performance, enjoyment, and player experience as well as reduce perceived workload compared to non-synchronized conditions. However, the effects seem to be strongly mediated by the player's conscious awareness of the synchronization. In the group of participants who did not correctly notice the synchronization differences between the experimental conditions, no significant effects could be found. Therefore, we advise researchers to take the individual capabilities of participants to perceive and move with the beat of the music into account when conducting studies involving the influence of music and rhythm.

The role of auditory-motor synchronization in the context of (exer-)games is still not understood very well. While the proposed study offers insights with regard to possible effects, future work should pay particular attention to potential mediating factors in the music, gameplay, and demographics. Furthermore, the effects of different relationships between the rhythm of music and gameplay should be considered, such as music tempo being faster or slower than the gameplay or dynamic changes in the relationship. Based on the present findings, we also plan to further examine the potential of rhythm and auditory-motor synchronization in exergames, for example, to facilitate memorization of movement patterns, offer additional auditory guidance to complement visually represented gameplay elements, or influence exercise intensity in self-paced exercise (for example, through spontaneous synchronization effects).

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