Setting the Stage: Using Virtual Reality to Assess the Effects of Music Performance Anxiety in Pianists

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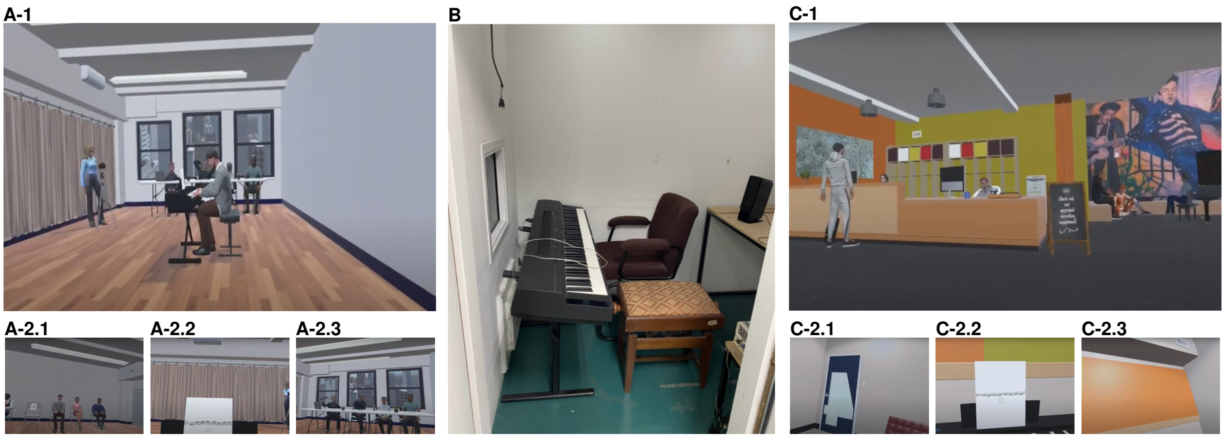

Figure 1: **Images of the VR stimuli and experimental room.** (A) Participant viewpoints in VR during the "Audition" (anxiety manipulation) condition and (C) the "Studio" (control) condition. (A-1, C-1) Viewpoint of the *Waiting* periods. In the subsequent *Lead-in* periods in VR, before transitioning immediately to the respective real-world piano performance tasks, (A-2.1, C-2.1) show left views, (A-2.2, C-2.2) show forward views, and (A-2.3, C-2.3) show right views. (B) Experimental room.

Abstract

Music Performance Anxiety (MPA) is highly prevalent among musicians and often debilitating, associated with changes in cognitive, emotional, behavioral, and physiological responses to performance situations. Efforts have been made to create simulated performance environments in conservatoires and Virtual Reality (VR) to assess their effectiveness in managing MPA. Despite these advances, results have been mixed, underscoring the need for controlled experimental designs and joint analyses of performance, physiology, and subjective ratings in these settings. Furthermore, the broader application of simulated performance environments for at-home use and laboratory studies on MPA remains limited. We designed VR scenarios to induce MPA in pianists and embedded them within a controlled within-subject experimental design to systematically assess their effects on performance, physiology, and anxiety ratings. Twenty pianists completed a performance task under two conditions: a public 'Audition' and a private 'Studio' rehearsal. Participants experienced VR pre-performance settings before transitioning to live piano performances in the real world. We measured subjective anxiety, performance (MIDI data), and heart rate variability (HRV). Compared to the Studio condition, pianists in the Audition condition reported higher somatic anxiety ratings and demonstrated an increase in performance accuracy over time, with a reduced error rate. Additionally, their performances were faster and featured increased note intensity. No concurrent changes in HRV were observed. These results validate the potential of VR to induce MPA, enhancing pitch accuracy and invigorating tempo and dynamics. We discuss the strengths and limitations of this approach to develop VR-based interventions to mitigate the debilitating effects of MPA.

Index Terms: Virtual Reality, Performing Arts, Virtual Characters

1 Introduction

The long-term deliberate practice of musicians is crucial for developing and maintaining their skills [26], yet factors such as pain, injuries, and performance anxiety can prevent them from fully demonstrating their abilities during critical moments. Music Performance Anxiety (MPA) is highly prevalent among musicians across all levels of expertise [12], often manifesting as intense fear and apprehension before or during performances [25]. Various factors – ranging from the size and atmosphere of the venue to the perceived stakes of the performance – can exacerbate the level of anxiety, and in extreme cases, leading to a withdrawal from their craft.. Although MPA can be debilitating [13], moderate levels of MPA can improve focus and motivation, contributing positively to overall performance [19, 25]. However, despite its widespread occurrence, research into MPA remains incomplete, particularly when compared to advances in our understanding of anxiety disorders [37]. Major challenges include limitations in assessing MPA in naturalistic settings due to logistical constraints and in laboratory environments that often struggle to effectively induce MPA [21]. This gap underscores the need for innovative approaches to studying MPA, such as the use of Virtual Reality (VR) technology [4, 5, 11], which offers a controlled and immersive environment to elicit and systematically assess the effects of MPA on musicians.

VR is a promising tool for inducing MPA as it can effectively replicate actual performance stages, audition spaces, and other rel-

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evant environments for musicians [4, 5, 11]. MPA-inducing VR settings could be valuable in two key contexts: (a) investigating MPA, and (b) modulating its detrimental effects through targeted interventions. While previous research addressing the second objective shows promise, the results have been mixed [4, 5, 29]. Limitations include the lack of suitable control conditions and gaps in identifying which specific performance aspects benefit from the intervention.

Our study aims to address two main research questions (RQs):

- **RQ1**: Can VR induce MPA in musicians? This should be reflected in an increase in subjective anxiety ratings.
- **RQ2**: What are the effects of VR-induced MPA on performance and cardiac physiology?

Based on previous work [11, 47], we designed and implemented two VR performance environments: one intended to induce MPA, modeled as an audition setting (**Audition**), and a control environment, modeled as a solo studio rehearsal (**Studio**). Additionally, drawing on findings that the waiting period before of a high-stakes performance – such as an audition, examination, or stage performance – is associated with higher anxiety ratings and physiological changes [9, 47], our VR environments were specifically designed to simulate the anticipatory phases of both an audition and a solo studio rehearsal. The experimental timeline for each condition included three parallel phases: a **waiting** period, a **lead-in** period, both inside a head-mounted display (HMD), and a final **performance** phase, outside of the HMD on a digital piano.

To address our RQs, and to validate whether the Audition condition induced increased experiences of MPA compared to the Studio one, we measured subjective anxiety ratings throughout these phases. We also measured participants' performance using MIDI (Musical Instrument Digital Interface) recording, and their physiological responses using an electrocardiogram (ECG).

If subjective MPA ratings are increased by the VR exposure (**RQ1**), we posit two hypotheses concerning how MPA influences musical performance and cardiovascular physiology (**RQ2**):

- **H1**: Relative to the Studio condition, the Audition setting will affect both error rates and the irregularity of timing intervals, both of which are markers of highly skilled performance[20, 38]. These measures will increase under detrimental VR-induced MPA effects and decrease under facilitatory effects.
- **H2**: Heightened anxiety states induced by the Audition condition will reduce time variation between successive heartbeats, termed heart rate variability (HRV), during the pre-performance period and, to a lesser degree, during performance, compared to the neutral Studio condition.

Contribution Statement. 1) We establish VR as a high-potential tool to address specific limitations of lab-based MPA research, implementing validated user journeys, environment designs, and data collection frameworks; and 2) we systematically quantify the effects of induced MPA on performance and cardiovascular physiology. Our findings reveal that under VR-induced MPA, participants improve performance accuracy (reduce error rates) faster than in the control VR condition. Additionally, they perform at a faster tempo with increased note intensity, indicating that MPA invigorates performance. This is, however, not accompanied by changes in HRV.

2 Related Work

2.1 Music Performance Anxiety (MPA)

MPA is highly prevalent among musicians, affecting more than 25% and spanning physiological, cognitive, emotional, and behavioral aspects [12, 13, 25]. MPA manifests as anxious apprehension towards performance, triggered by evaluative threats and exacerbated by a competitive music industry, perfectionist traits, and lifestyle factors [12, 19, 25]. Common responses include fear, panic, stress, and mood swings, which promote avoidance and safety behaviors like substance use, as well as dysfunctional beliefs about performance inadequacies. These effects can drastically reduce concentration, confidence, and creativity, degrading performance quality and adversely affecting musicians' well-being, health and career trajectories [12, 19, 25].

How does MPA modulate performance? Models and empirical studies have shown divergent effects of MPA on musicians: while some experience performance decrements under high MPA, such as increased muscle stiffness and impaired memory recall [1, 21], others continue to excel, challenging the view that high MPA levels necessarily hinder performance [19, 24, 31]. However, it remains unclear which specific factors contribute to beneficial or detrimental effects of MPA on performance quality, well-being, and enjoyment.

Understanding the effects of MPA on performance could be improved by simultaneously assessing physiological changes [16, 17]. The physiology of MPA includes various responses to perceived threats, such as cardiovascular symptoms like tachycardia and high blood pressure, and respiratory changes such as hyperventilation [12, 19, 25]. These physiological alterations can compromise performance by affecting fine motor skills. However, the relationship between physiological responses and MPA levels is not fully understood. Elevated heart rate and blood pressure do not always correspond with high levels of reported MPA [21, 44], and physiological arousal can sometimes enhance performance. It has been proposed that assessing whether performers perceive a situation as threatening or challenging can clarify the effect of MPA on performance and body physiology [17]. These insights highlight the need to address both the physiological and psychological components of MPA, alongside a systematic assessment of performance.

Heart rate variability is a useful metric for assessing physiological changes during MPA [45]. HRV reflects the complex modulation of heart rate by autonomic, respiratory, circulatory, endocrine, and mechanical influences over time [32, 36]. Biobehavioral frameworks indicate that reduced HRV reflects an inability to suppress maladaptive cardiac responses to stress and threats, whereas increased HRV facilitates behavioral adaptation and cognitive flexibility [34, 43]. Reduced HRV is associated with poor cardiovascular health and is also used to detect variations in mental disorders and cognitive impairments [33]. HRV measurements have proven effective in MPA studies, showing significant reductions in HRV complexity under high-stress conditions during realistic stage performances [9, 48]. More broadly, lower HRV is associated with greater symptom severity in mood and anxiety disorders, and impaired cognitive performance in anxious states [18, 42]. Accordingly, HRV metrics provide a suitable index of cardiovascular physiology for assessing the somatic manifestations of MPA, both in anticipation of and during performance.

2.2 VR and Music Performance

VR technologies have been leveraged for both entertainment and practical applications in creating, learning, and performing music. Consumer applications such as Virtuoso [1], an immersive VR musical sandbox game, allow users to create music across a range of instruments uniquely designed for VR. In addition, the mixed reality application PianoVision [2] is positioned as a 'VR Music Teacher' for piano that can connect to a MIDI piano or a flat surface to augment note visualizations, fingerings, and provide real-time feedback. In previous research, Johnson and colleagues [22] compared the effectiveness of traditional and virtual training environments (both immersive and non-immersive) for the theremin musical instrument.

[1] https://virtuoso-vr.com/
[2] https://www.pianovision.com/

They found that the immersive VR environment resulted in significantly fewer performance errors during training. Unexpectedly, however, this effect did not carry over to post-training real-life performances. Ppali and colleagues further developed a VR system for musicians to rehearse and perform in three different environments: an orchard, a performance venue, and an apartment with plants [35]. The focus of their work was to use VR to facilitate creative musical practice. Ongoing developments in the growing field of Music and VR promise more innovative applications in the future.

2.3 VR for Anxiety Disorders and MPA

VR has been effective in managing anxiety in cases of generalized anxiety disorder and social phobia, and has been beneficial for the general population by simulating public speaking and other anxiety-inducing situations (For a review, see [40]). These applications emphasize the potential of VR to create controlled, yet realistic environments where individuals can safely confront their anxiety, thus facilitating improved outcomes in therapeutic settings [6].

The use of VR in inducing and assessing anxiety in skilled musicians has gradually gained traction [4, 5, 11, 30]. Recent developments in mixed reality for inducing MPA have shown that these settings enhance realism, potentially eliciting experiences akin to those in real performance scenarios [30]. High degrees of realism have become a primary consideration in the development of MPA training and management applications, particularly in performance settings that include some form of evaluation, such as concerts or auditions, which have been especially effective in eliciting MPA compared to unobserved, home-like settings [11]. Notably, Fanger and colleagues' PIANX platform immersed users in virtual performance environments while wearing an HMD, displaying the user's real-world hands and piano keys within the VR environments, and provided real-time feedback based on MIDI data [11]. They found that musicians preferred seeing their real hands in a mixed reality setting rather than virtual hand representations and successfully modulated anxiety levels with their VR platform, although the effect of induced anxiety on performance was not directly assessed.

From another perspective, VR has been examined as an intervention to manage MPA. Focusing on a pre-performance phase, van Zyl examined the effects of VR 'relaxation' sessions on MPA symptoms in various instrumentalists before performances [49]. Participants in the treatment group, who selected one of three VR environments (beach, meadow, or desert) for a 5-minute exposure, reported significantly lower anxiety levels, although the small sample size (N = 6) was a limitation. In a study by Bissonnette and colleagues, a CAVE-like system served as a training environment for pianists to practice between two real-life performances [4]. Those who participated in the VR sessions reported reduced anxiety levels and showed significant improvements in performance quality compared to a control group that received no intervention. However, the small sample size (N = 9 for VR, N = 8 for control) and lack of an active VR control raise the possibility of a placebo effect. Currently, an ongoing clinical trial scheduled for 6 months is investigating the efficacy of VR Exposure Therapy in reducing MPA symptoms compared to progressive muscle relaxation (PMR) techniques [2], utilizing both performance assessments and HRV data.

Crucially, despite advances in developing VR applications to induce MPA for training musicians, previous research has not examined the potential of VR to overcome laboratory limitations in studies specifically designed to induce MPA and assess its effects on subjective experiences, performance, and physiology. Our work aims to bridge this gap by utilizing questionnaires, performance data (MIDI recordings), and physiological measurements (ECG).

3 METHODS

3.1 Participants

Twenty participants (12 females, 8 males, average age 25.1 ± 1.17 years [standard error of the mean, SEM], range 18 – 35 years; 18 self-reported right-handed, 2 left-handed) were recruited for our study through notice boards and social media. All participants were required to have at least six years of formal piano training, with an average of 15.6 years ± 1.22 years, ranging from 8 to 25 years. The majority had at least prior VR experience. Participants received a maximum compensation of £30.

Explicitly informing participants of the rationale for exposing them to anxiety-inducing environments was crucial, given the potential risk of physical or psychological distress or discomfort. We implemented proactive measures allowing participants to opt out at any time and provided access to mental health resources. Informed consent was obtained from each participant. The study received approval from the Research Psychology Department Ethics Committee of Goldsmiths University of London.

3.2 Experimental design and performance material

We designed a within-subject study in which participants completed a real-world piano performance task immediately after experiencing a simulated pre-performance sequence in VR in two conditions:

- **Audition:** Public Audition Condition (Anxiety manipulation)
- **Studio:** Private Rehearsal Studio Condition (Control)

The rationale for designing these scenarios was based on previous work, which revealed that audition settings are effective at inducing anxiety in musicians, while solo performances serve as the suitable corresponding control condition [9, 11].

The performance tasks involved two right-hand excerpts adapted from Prelude V of the Well-Tempered Clavier (Part 1) by J. S. Bach, used in previous work [8, 38]. Each was played at a tempo of 65 BPM per quarter note and matched in length and difficulty. These sequences consisted of 32 sixteenth notes with regular (isochronous) intervals between consecutive notes, 230 ms (Inter-Onset-Interval, IOI). Two alternate melodies were used in cases where participants had prior exposure to the primary melodies, specifically using two excerpts from the Piano Sonata No. 52 in E Flat Major by J. Haydn. The length, note duration, and tempo instructions for these alternate melodies were identical to those of the primary melodies. The number of participants completing each set of melodies was:

- **Melody 1, Melody 2**: Primary Melodies (N = 16)
- **Melody 3, Melody 4**: Alternate Melodies (N = 4)

Participants had to play these melodies using the score across 15 trials (repetitions) in both the Audition and Studio conditions. The mapping between melody, VR environment, and the order of the condition was pseudorandomized and counterbalanced across participants.

3.3 VR Scenario Development

The application was developed using Unity [3]. It used both the Oculus Integration SDK (version 41.0) and Unity XR Plug-in Management package with hand tracking enabled. The Meta Quest 2 [4] (MQ2) device was used for deployment. All experiential versions were integrated into a single build with a selector to set participants up for the correct VR sequence. Humanoid avatars were sourced and imported from Ready Player Me [5] and Mixamo [6], with Mixamo

[3]https://unity.com/
[4]https://meta.com/gb/quest/products/quest-2/
[5]https://readyplayer.me/
[6]https://www.mixamo.com/

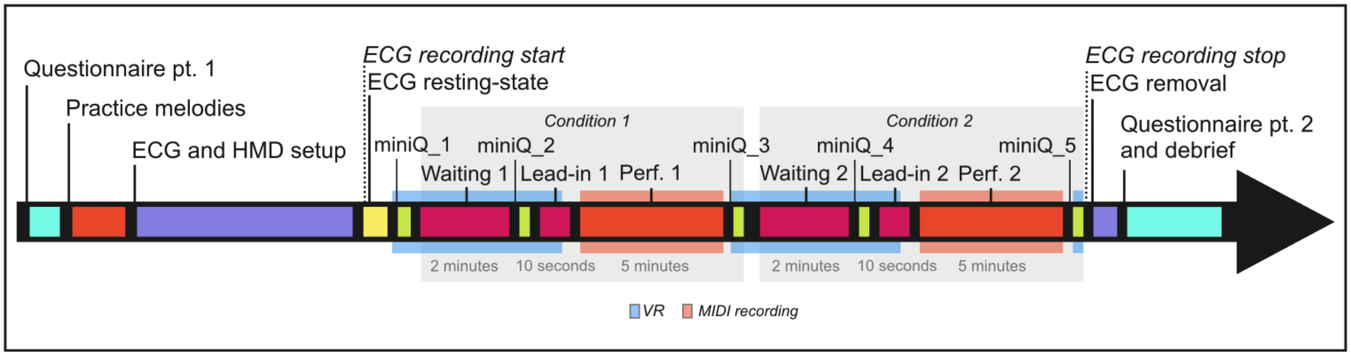

Figure 2: **Timeline of the procedure**. Each participant went through both conditions, in pseudorandomised and counterbalanced order. Each condition includes a VR **Waiting** period, VR **Lead-in** period, and real-world **Performance** period

animation clips modified in Unity through keyframe adjustments. Digital assets from the Unity Asset Store [7] and TurboSquid [8] were modified (a list of digital assets used can be found in Supplementary Materials). Custom assets were modeled in Autodesk Maya [9].

3.3.1 MPA Factor Design

To design the VR audition scenario in such a way that it triggers performance anxiety in musicians, we searched for related terms on social media platforms commonly used by musicians. Specifically, MPA factors were sourced through YouTube videos where content descriptions related to “overcoming”, “managing”, and “tips for” MPA were searched. Comments and replies were systematically examined by researchers to identify recurring themes and patterns in MPA experiences, and isolate specific MPA factors. Examples of factors integrated into our VR audition room design include: “a large space”, “waiting to perform in a shared space after a skilled performer”, “seeing other people displaying signs of nervousness”, and “being recorded while performing”. We excluded certain MPA trigger factors, such as “temperature discomfort” and “the need for beta blockers”, which were less relevant to our VR implementation. The identified factors align with previous qualitative assessments of MPA triggers in musicians [24, 25]. Refer to the table in the Supplementary Materials detailing our MPA Factors design.

3.3.2 VR Scenarios

Two VR scenarios were designed and implemented for the two conditions: Audition and Studio. Each condition consisted of a *waiting period* (two minutes) and a *lead-in period* (ten seconds) (Figure 2). Here we summarize key points of each scenario; see further details in Supplementary Materials and our walk-through video.

The setting for the virtual **Audition** environment was designed to replicate a top-tier audition studio (Figure 1 A). The participant entered VR and began the *waiting period* as seated in a row of five folding chairs. The room was filled with the sound of a Bach prelude being performed by another auditionee, at high-volume and a high performance level, on the digital piano in the center of the room in the participant’s forward line of sight. The participant could also see a camera woman filming the performing auditionee, and a coordinator with three judges sitting across the room, who occasionally whispered to each other. There were other auditionees sitting next to the participant; notably the participant on their right-hand side appeared to be very nervous, looking down and moving back and forth. After approximately two minutes, the auditionee finished, and the participant was called. The previous auditionee, still seated at the piano, relaxed back and turned to look at the participant in the last seconds of the waiting period. For the *lead-in period*, the participant was re-positioned and seated on the piano bench at the piano in the center of the room. On the piano stand in front of them was the sheet music for the performance task melody and the room began to fade out. The participant was in close proximity to the judges panel, now on their right, and the coordinator gestured and said, “Okay, I think we’re ready now... We’d...first like to hear the piece you prepared”. The judges appeared unenthusiastic, and the camera operator in front of the piano rocked back-and-forth, looking down with arms crossed.

The virtual **Studio** environment was designed to replicate an inviting off-site music rehearsal studio (Figure 1 C). The participant began the waiting period in a vibrant open lobby, seated alone on a red couch. An upbeat, instrumental music track was played overhead at a moderate level. The participant’s view was split between a lounge and a distant reception area, populated with several virtual characters who appeared relaxed and were engaged in friendly conversation; their chatter was subtly audible. After approximately two minutes, a receptionist stood up, faced the participant, and said from behind the desk, “Hey, the studio you booked is open now. It’s at the end of the hallway on your left, and if you need anything... let us know”. This marked the end of the *waiting period*. During the *lead-in period*, the participant was re-positioned in a new space which is a small, quiet, and private rehearsal studio with a closed frosted glass door. The participant was seated at the digital piano where the sheet music for the performance task melody was placed on the music stand, and the room began to fade out without interruptions.

3.3.3 User Experience Design

The study was designed to allow participants to complete each condition without requiring real-world intervention for guidance, as the risk of interruption would break the sense of immersion and presence that VR aims to create. The VR experience was untethered, and Meta Quest app casting was used for the experimenter to monitor the progress and on an iPhone 11. Participants could trigger the condition scenes when they were ready with a right-hand thumbs up gesture which was implemented using OVRHand. There were also short Questionnaires embedded in the VR experience (see Section 3.5 and Figure 3). The submit button would then trigger an automatic loading of the subsequent scene in the experiment. A VR User Demo scene was created and used ahead of the experiment to familiarize participants with the relevant gestures, interactions, and indicators for seamless navigation through the experiment.

We used VR Pass-through technology to manage the transition from the VR environment to the real world, by overlaying the virtual content with real-world visuals at the transition period. Upon

[7] https://assetstore.unity.com/
[8] https://www.turbosquid.com/
[9] https://www.autodesk.com/products/maya

completion of the VR session, a 'glowing' green light pass-through indicator was activated through the Passthrough API, guiding participants to remove their headsets and proceed to the real-world piano performance task. A red light indicator signalled the end of the performance session.

3.4 Performance and ECG recording

The experiment was carried out in a dimly lit and acoustically shielded room, where the pianists sat comfortably in front of a digital piano (Yamaha Digital Piano P-255) in an armchair. Their ECG was recorded continuously during the experimental session using an electroencephalography (EEG) system (ActiveTwo, BioSemi Inc.) placed in an electromagnetically shielded room. The ECG was recorded using two external channels with a bipolar ECG lead II configuration (the negative electrode was placed on the chest bellow the right collar bone, and the positive electrode on the left leg above the hip bone). During the recording, the data was high-pass filtered at 0.16 Hz and sampled at 1024 Hz. The ActiveTwo, BioSemi ground electrodes (CMS, DRL) were placed on the left forearm. ECG were saved in the BioSemi Data Format (BDF). A single BDF file per participant was used to record ECG throughout the entire experiment, with function key press triggers used to segment the recording for data cropping.

Performance was recorded as MIDI files using Visual Basic software alongside a standard MIDI sequencer program on a PC running Windows XP. To manage the behavioral paradigm and record the MIDI data, we utilized custom-written code in Visual Basic [8, 38]. This code presented performance instruction cues visually, which were displayed on a PC monitor (angle 4°) located on the wall behind the piano (see 1B and section 3.6). The software also facilitated the transmission of synchronization signals in the form of transistor-transistor logic (TTL) pulses. These pulses corresponded to the onsets of visual stimuli, key presses, and metronome beats, and were sent to the ECG acquisition PC.

3.5 Subjective ratings

To validate that the Audition condition in VR elicits increased anxiety, we collected subjective anxiety ratings using a modified version of Cox's Revised Competitive State Anxiety Inventory-2 (CSAI-2R) [10], originally designed to assess competitive performance anxiety in athletes. The CSAI-2R includes 17 items rated on a 4-point Likert scale, measuring 'somatic anxiety' (i.e. physiological), 'cognitive anxiety' (e.g. worry), and self-confidence. Modifications included rephrasing directions and altering two statements: 'competition' to 'performance' (Q2) and 'losing' to 'not succeeding' (Q5).

Inside VR, participants were presented with paired statements from the modified CSAI-2R, referred to as *miniQ_1* through *miniQ_5*, consisting of one somatic and one cognitive anxiety statement (see Table 1 and Figure 3). These were delivered consistently five times for each participant at specific points (see Figure 2). Our primary measures were the subjective anxiety ratings for somatic and cognitive anxiety during the *post-waiting* period, normalized to baseline *pre-exposure* values (post - pre). This normalization procedure thus revealed changes post- relative to pre-VR exposure in each condition. We expected higher normalized anxiety ratings in the Audition compared to the Studio VR condition, validating that the Audition VR setting successfully induced performance anxiety.

After the experiment, participants completed the State-Trait Anxiety Inventory (STAI) [41], which assesses general anxiety using a 4-point Likert scale. They also filled out questionnaires evaluating the effects of VR design elements in both conditions, rated on a 5-point Likert scale across five areas: *Environment Perception*, *Targeted MPA Feelings*, *Sense of Time*, *Avatar Presence*, and *Procedure Progression*. They were asked to identify which elements contributed most to calmness in the Studio environment and anxiety in the Audition environment, and rate the VR experience for its potential in musicianship development and MPA training. A final open section recorded improvement feedback.

Table 1: Subjective Anxiety Measurement (miniQ)

Anxiety Component	Statement
Somatic anxiety	1. My heart is racing.
Cognitive anxiety	2. I'm concerned about performing poorly.

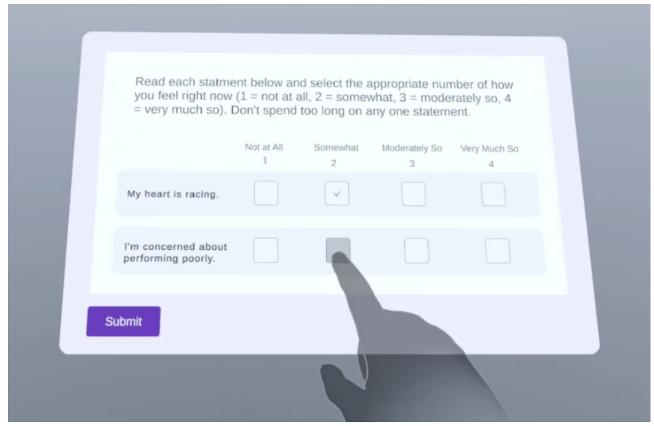

Figure 3: **miniQ display and interaction in VR**

3.6 Procedure

Upon arrival, participants filled out the initial paper questionnaires, then were escorted to the digital piano in the EEG lab for a 5-minute private familiarization with the pieces using the musical score. For the first 4 minutes, they played at their own pace, then followed a metronome set to 65 BPM for the final minute. They were advised to maintain this tempo during recorded performances, see below.

Participants were then fitted with the ECG electrodes. ECG recording commenced and continued throughout the experimental session, including several **phases**: a 5-minute resting state, a 2-minute VR pre-performance *waiting* period in either the Studio or Audition setting, a 10-second lead-in phase (not analyzed), and a 5-6 minute real-world piano performance phase. The experimenter used the PC keyboard to mark the start and end of each phase in the ECG recording.

For HMD setup, we used the EyeMeasure [10] app on an iPhone 11 to capture participant's inter-pupillary distance (IPD) and adjusted the lens spacing on the MQ2 according to Meta guidelines [28]. Participants wore a disposable VR face mask for hygiene, and we adjusted the MQ2, including adding a glasses spacer if needed. Once in VR, we instructed participants to remain seated, restrict drastic arm movements (to avoid collisions with real-world objects not reflected in VR), and look around in all directions of VR environments. The participant was then guided through the VR User Demo scene. Next, the experimenter exited, closing the door. Participants then signaled readiness by giving a thumbs-up, initiating the first experiment condition.

In VR, participants answered *miniQ_1*, after which the waiting period scene automatically loaded. They remained seated for the 2-minute duration. Upon completion, *miniQ_2* was displayed. After answering, the lead-in period VR scene was automatically loaded. Participants remained seated at the piano in the scene for the 10-second fading duration. The pass-through performance transition indicator scene appeared, and participants removed the MQ2, placing

[10] https://apps.apple.com/us/app/eyemeasure/id1417435049

it in a holding area next to the piano, while we launched the MIDI recording via our custom program.

The experimental performance task consisted of 15 trials, using a synchronization-continuation paradigm [8, 38]. The musical score was displayed on the music stand of the piano. Each trial was initiated by participants pressing a designated key with their left index finger. It began with four metronome clicks at 65 BPM to entrain participants to the instructed tempo, followed by them playing the excerpt once while a green ellipse indicated recording, and stopping when it turned red (after 10 seconds). No metronome ticks were used during the performance.

After completing the first performance condition, the participant put on the MQ2 for the second condition, playing the second melody following the same steps. Upon completion, the ECG electrodes were removed, and the participant completed the final questionnaires, received debriefing, and compensation details..

3.7 Performance Analysis

Data analysis of the MIDI files categorized errors as incorrect pitches and identified correct notes as key presses accurate in pitch, with IOI values under 500 ms. This setup aligns with the specified tempo (65 BPM per quarter note, approximately 230 ms IOI between key presses), but allows for timing variations inherent in performing these pieces from the score for the first time.

We utilized a custom-based MATLAB algorithm to compare each MIDI performance with its template for pitch accuracy [8, 38]. Our dependent variables (DV) were the average tempo of correct notes (mean IOI, mIOI), coefficient of variation of IOI (cvIOI) assessing timing variability, the average keystroke velocity (MIDI velocity, related to note intensity or loudness), the rate of correct notes (accuracy rate), and the error rate. We also analyzed changes in error rate across trials to assess improvements with practice in each VR setting. Using various DVs allowed us to test **H1** and to determine whether the targeted MPA effects on performance were limited to the hypothesized variables or extended to others. Additionally, to verify that participants adapted their performance during learning, we analyzed whether pitch errors were followed by a tempo reduction (post-error slowing), alongside reductions in tempo and keystroke velocity at the error itself, reflecting rapid online adjustments during the performance [8, 38].

3.8 Heart Rate Variability

We assessed physiological changes during VR-induced anxiety by measuring various HRV metrics [32, 36]. As reviewed in section *Related Work*, individuals in anxiety states typically exhibit decreased HRV compared to those in neutral conditions. Research using entropy-based HRV metrics, like fuzzy entropy or multiscale entropy, has demonstrated HRV reduction during stressful simulated auditions and an actual stage performance [9, 48].

Here we focused our analysis on three robust HRV metrics, (i) the time-domain mean of the R-R interval distribution excluding outliers (Figure S1AB), MeanNN; this metric relates to the heart rate; (ii) the frequency-domain high-frequency HRV (HRV-HF; Figure S1C), denoting parasympathetic activity (body's relaxation responses), and (iii) the Fuzzy Entropy HRV metric. The ECG signals were processed using NeuroKit2 [27], a widely used open-source Python package (version 0.2.7). This package was used to pre-process the continuous ECG signal, segment it into each experimental phase (rest, pre-performance and performance, in studio or audition environments), and extract the distribution of R peaks (Figure S1).

In two participants, Neurokit2 was unable to identify valid R peaks in one of the extracted ECG signal segments. Additionally, ECG recordings were lost for one participant. Due to issues with the MIDI recording, we also excluded the ECG data from participant #5. Consequently, this resulted in a balanced dataset of HRV values across the VR Audition and Studio settings for N = 16 participants.

3.9 Statistical analysis

Analysis of the subjective ratings, behavioral, and HRV data was conducted using non-parametric permutation tests in MATLAB. Central advantages of using permutation tests include robustness against small sample sizes and outliers [15]. They rely on the assumption of exchangeability between observations (and same variance of distributions), which was met. Here, within-subject analyses contrasting our dependent variables across Audition and Studio conditions were performed using a ranked permutation test with n = 5000 permutations, drawn at random from the complete permutation distribution (n = 2^{20}, Monte Carlo permutation test). We utilized the difference between condition means as the test statistic. Our alpha level was set at 0.05. For multiple comparisons, an adaptive two-stage linear step-up procedure was applied to control the false discovery rate (FDR) at the specified level [3]. P-values after FDR control are denoted by P_{FDR}.

Prior to the statistical analysis, anxiety ratings and HRV values were normalized by subtracting the initial baseline values. For anxiety ratings, this involved a post-minus-pre VR exposure transformation. For HRV, we subtracted the baseline resting state HRV from the pre-performance values (VR exposure: waiting) period and from those measured during the performance period.

Permutation tests were complemented with Bayes Factor (BF) analysis using the Bayes Factor toolbox for MATLAB [11]. In the case of non-significant differences, we used BF_{10} to estimate the degree of evidence in support of the null hypothesis H_0, representing no difference between conditions, or the alternative, denoting between-condition differences. BF_{10} values were interpreted following [46]

To assess how VR conditions modulated learning effects across trials, we employed Bayesian hierarchical beta regression models, using the error rate as the dependent variable (range 0-1), conducted with the R package brms [7]. Effects of the Bayesian regression models are reported as posterior means and 95% credible intervals (CrI). When the 95% CrI overlaps with zero, it suggests that the true value of the effect could be zero, indicating no meaningful effect.

4 Results

Throughout, we provide data as mean and SEM. Participants generally disagreed with the statement that they had come across a similar VR experience in their years of playing piano (Q2-IX: VR Experience, mean = 2.00, SEM = 0.2).

4.1 Validation of anxiety induction

Statistical analysis of the somatic and cognitive anxiety ratings collected throughout the experimental phases (see Figure 2) revealed that the exposure to the Audition VR setting significantly increased subjective somatic anxiety ratings relative to the Studio VR condition ($P_{FDR} = 0.0114$). This result is visualized in Figure 4A, which displays normalized *post-waiting period* somatic anxiety ratings against the *pre-exposure* values (see details in the Statistical Analysis section). By contrast, cognitive anxiety ratings were similar between the Audition and Studio VR conditions ($P_{FDR} = 0.5226$, anecdotal evidence for similar values, BF_{10} of 0.3436; Figure 4B).

Thus, the effect of VR on increasing subjective anxiety ratings was specific to somatic, not cognitive anxiety. General trait anxiety levels were moderate towards high (mean 42.90, SEM 2.5; [41]).

4.2 Behavioural results

The pianists played the musical excerpts at the instructed tempo (average time between consecutive notes, or inter-onset-interval, IOI, was 236 [13] ms), when excluding pitch errors in the analysis. One pianist played the melodies at a slower tempo (mean IOI around 400 ms), but they were not excluded from the analysis. On average, pianists accurately played 81.21% (3.3%) of notes both in

[11] `10.5281/zenodo.4394422`

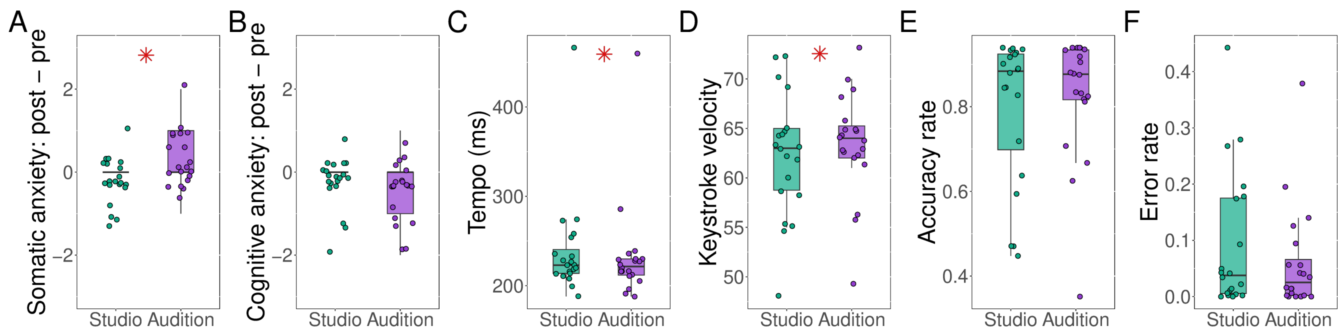

Figure 4: **Change in subjective anxiety ratings and effects on performance. (A-B)** Anxiety scores for selected somatic and cognitive anxiety items. The *post-waiting period* scores were normalized by subtracting the values of the corresponding *pre-exposure* measurement (shown as post-pre in the figure). Normalized scores for somatic (A) and cognitive (B) anxiety items, shown as a boxplot and individual data points, N = 20. The red asterisk denotes significant differences in the dependent variable between the Audition (purple) and Studio (green) VR conditions. See main text. The Audition relative to the Studio VR exposure did not modulate cognitive anxiety ratings. No significant between-condition differences were found in this phase; anecdotal evidence for the null hypothesis. **(C-F)** Effect of anxiety induction on performance, displayed along relevant performance variables: mean tempo, keystroke velocity, accuracy rate, error rate.

pitch and timing. This analysis excluded events that were correct in pitch but featured outlier latencies above 500 ms, suggesting potential cognitive or action monitoring delays. These events were further analysed to assess the impact of our anxiety manipulation on tempo and keystroke velocity. Regarding pitch errors, participants committed errors in 7.69% (2.1%) of cases. Of these, only 1.39% (0.04%) were isolated pitch errors—incorrect notes surrounded by at least three preceding and following correct events. These so-called isolated pitch errors helped confirm that our paradigm replicated known behavioural effects of skilled piano performance and error monitoring, as documented in previous studies [8, 38]. Specifically, we observed that isolated pitch errors and keystrokes following pitch errors were slower (error-slowing: $P_{FDR} = 0.0270$, mean tempo 265.7 [14] ms relative to that of correct events, 234.7 [13]; post-error slowing: $P_{FDR} = 0.0002$, 327.7 [45] ms, compared to correct events). Additionally, there was a trend towards a significant reduction in keystroke velocity during pitch error events ($P_{FDR} = 0.0996$, MIDI velocity 60.41 [1.6] a.u. at pitch errors, 62.46 [1.2] a.u. at correct notes) previously suggested to indicate cognitive control mechanisms intended to halt error execution [8, 38].

Next, we addressed our hypothesis that induced anxiety modulates specific performance variables: average tempo, timing variability, keystroke velocity, and the accuracy and error rates, as illustrated in Figure 4C-F. Participants significantly played faster in the Audition than in the Studio condition ($P_{FDR} = 0.0154$, 230.1 [13] ms and 239.4 [13] ms; Figure 4C). They also significantly increased keystroke velocity when playing the melodies under anxiety induction ($P_{FDR} = 0.009$, 63.1 [1] a.u. and 61.8 [1] a.u.; Figure 4D). By contrast, the timing variability (cvIOI), accuracy, and error rates did not show significant differences between conditions ($P > 0.05$; Figure 4EF; anecdotal evidence supporting the null hypothesis: BF_{10} around $0.35 - 0.49$ for these dependent variables).

Assessing learning effects across the 15 trials, using Bayesian hierarchical beta regression models with trial and condition as fixed effects and subjects as random effects, we observed that participants overall reduced the error rate across trials(Figure 5A; credible effect for a negative slope, -0.04142, with 95% CrI, [-0.08291,-0.00005]). The average error rate was similar between VR conditions (Figure 5B, where the 95% CrI overlapped with zero). Crucialy, however, across trials, the error rate decreased faster for the Audition than for the Studio condition (Figure 5C; credible effect of the Audition relative to the Studio condition on reducing the slope: -0.05617, 95% CrI = [-0.10608 -0.00626]).

These results suggest that our anxiety manipulation specifically modulated keystroke dynamics and average tempo, without affecting *average* pitch accuracy, error rate or timing variability. Moreover, MPA induction improved learning of the melodies, reducing the error rate across repetitions in the Audition relative to the Studio condition.

4.3 Heart rate variability

The HRV metrics obtained during the pre-performance and performance phases in each VR condition were normalized by subtracting the resting state HRV values. The normalized HRV index during the pre-performance period did not show significant differences between the Studio and Audition conditions across any of our metrics, including MeanNN, HRV-HF, and Fuzzy Entropy. The p-values were all above 0.05, and BF_{10} were in the range 1/10 to 1/3, providing substantial evidence that HRV metrics were comparable in both conditions [46]. Similarly, no significant differences were found between conditions during the performance phases ($P > 0.05$, and BF_{10} in range 0.1 - 0.33). See Figure 6 (pre-performance and performance phases are labelled 'Waiting' and 'Playing' for conciseness). Exploratory analysis showed no significant VR-related modulation of HRV relative to the initial resting state (p = 0.1048–0.7606).

4.4 VR Experience Questionnaires

Among all VR experience statements, only those in the *Targeted MPA Feelings* category exhibited significant statistical differences between conditions, thereby aligning with the intended design and aim of the study. On average, scores for statements related to MPA and stress during waiting and transition periods were greater in the Audition than the Studio environment (significant difference, $P_{\text{FDR}} = 0.0002$). Specifically, participants reported that the Audition environment invoked greater feelings of MPA (mean [SEM]: 3.35 [0.23] vs. 2.20 [0.21]), and had both a more stressful waiting period (3.10 [0.19] vs. 1.95 [0.20]) and lead-in period (3.50 [0.21] vs. 1.95 [0.23]) compared to the Studio environment. Conversely, the Studio environment showed higher scores for statements about feeling calm during the waiting period (4.15 [0.13] vs. 2.85 [0.24]), significant difference, $P_{\text{FDR}} = 0.0002$) and the lead-in period (3.90 [0.20] vs. 2.45 [0.22], significant difference, $P_{\text{FDR}} = 0.0012$). The remaining statements in categories outside of *Targeted MPA Feelings* were associated with non-significant differences ($P > 0.05$ in all cases, BF_{10} in range 0.1-0.4, denoting substantial and anecdotal evidence for no differences). See further details in Supplementary Materials.

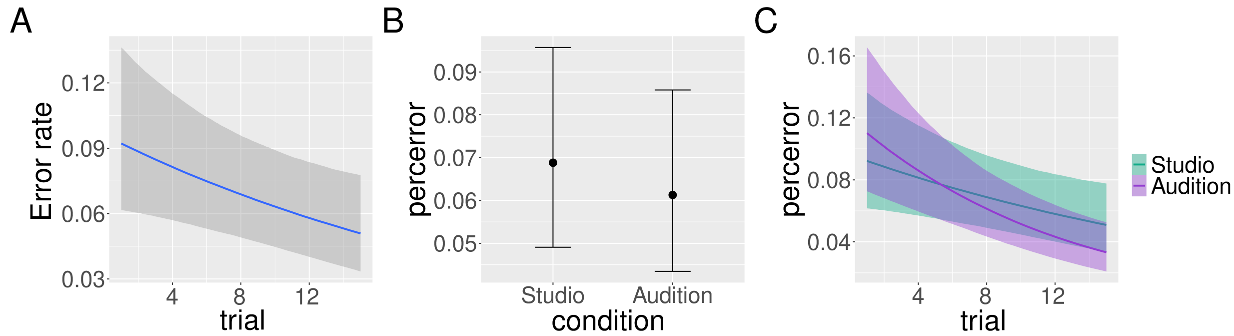

Figure 5: **Effect of VR condition on error rate over repetitions (A-C)** Error rate over 15 trials: overall decrease (A), similar mean rates across conditions (B), faster progression to a more accurate (reduced error rate) performance in the Audition vs. Studio condition (C).

In the Studio environment, participants rated the 'lobby music playing in the background' as the most calming element in the environment (N = 12), followed by 'the decor' (N = 3) and 'the colors' (N = 3), 'the outside greenery' (N = 1) and 'other' (N = 1: 'being in a relatively unnoticed spot where no one is paying attention'). In the Audition environment, the 'judges panel' was rated as the element contributing most to MPA (N = 8), followed by 'hearing the performance of the pianist ahead of them' (N = 5), 'other' (N=4), 'performances being filmed' (N = 2), and 'performing in front of other pianists' (N = 1). Of the 'other' responses, three indicated 'the pianist next to them acting anxiously' and one specified 'someone looking from the door'.

4.5 Participant Feedback

Several participants expressed unease about potential judgment upon arriving at the lab. One participant reported feeling anxious after the practice session and tried deep breathing during the resting phase, suggesting the setup may have elevated anxiety levels.

Five participants commented that they would prefer to have the entire experiment within VR. They acknowledged an 'effect' from the VR, but noted that the sensation 'disappeared' once the HMD was removed for the performance tasks, returning their awareness to the real world. They felt that performing within VR would be 'more realistic' and would 'impact feelings of anxiety more'.

Participants also commented on realism improvements for the VR environments centered around the replacing the use of the Ready Player Me avatars (N = 3) that appeared cartoon-like, making one participant feel like they were 'in a game', and a preference for 'real' video-based VR elements (N = 2). No direct feedback disputing the plausibility of the Audition and Studio settings was received. However, for the Audition environment, some participants desired more interaction and dialogue (N =2) and an overall heightened sense of 'real' judgement from others of their performance (N = 3).

5 Discussion

Our VR implementation effectively met our primary objective, inducing higher MPA in the Audition compared to the Studio condition. By employing the separate somatic and cognitive components of a validated competitive (performance) anxiety scale [10], the analyses revealed significantly higher somatic ratings in the Audition environment, with no changes in cognitive anxiety. This outcome indicates that our VR design specifically targeted the physiological manifestations of anxiety, leaving worry and other cognitive aspects of MPA unaffected, thus expanding on prior work that assessed anxiety as a single dimension [4, 5, 11]. External pressure to perform well was likely minimal, as the performance tasks involved no stakes or rewards, and participant feedback indicated that the melodies, at the required tempo, were of low difficulty given their experience levels. By manipulating the performance components alongside the VR design, future work could thus explicitly target somatic or cognitive components of anxiety and assess their separate effects on performance, subjective experiences and physiology.

The performance data showed that VR-induced MPA speeded the performance tempo and increased the velocity of key presses in the Audition compared to the Studio condition. This effect may reflect invigoration caused by MPA, aligning with research that suggests anxiety can speed up performance [23], potentially due to heightened arousal. Notably, such MPA-related invigoration effects have not been previously reported and could serve as valuable dependent variables in future MPA research, offering additional insights into performance changes to the general 'performance quality' metrics typically used [4, 5]. Recent research indicates that anxiety induction (via threat of shock) leads to an underestimation of time intervals, making "time fly", in contrast to fear, which slows time perception [39]. An interesting direction for future MPA research could be to examine whether the increased performance tempo observed in our study, under conditions of heightened somatic anxiety, might be attributed to a temporal underestimation of performance intervals, potentially influenced by changes in attentional processing [39].

Furthermore, participants in the Audition condition improved their performance accuracy more rapidly across repetitions, achieving lower error rates by the end of the session, in line with **H1**. This suggests enhanced learning under heightened somatic anxiety, underscoring the potential of our VR design in contributing to training and learning contexts. Crucially, although participants expressed a preference for completing performance tasks in VR with the HMD on, previous work has highlighted participants' preference for seeing their own hands rather than virtual hand representations[11]. Our data thus suggest that isolating VR exposure just before real-world performance could be a practical approach for studying MPA, effectively simulating and examining the conditions that induce MPA.

Contrary to our second hypothesis (**H2**), HRV metrics were comparable between the Audition and Studio conditions, based on Bayes factors. Despite higher somatic anxiety ratings and elevated VR Experience scores on Targeted MPA Feelings in the Audition setting, HRV did not emerge as a reliable measure of physiological anxiety state changes. Additionally, HRV during VR exposure remained unchanged from the initial resting state. Similar inconsistencies have been observed in prior studies [36], which may stem from a limited sensitivity of HRV to differentiate between perceptions of performance as a challenge or a threat [17]. Specifically, while our VR design may have induced adaptive forms of MPA, characterized by increased arousal and somatic anxiety, it did not necessarily induce debilitating forms of MPA that perceive performance as a threat. Previously reported decreases in HRV in anxiety may also involve changes in cognitive anxiety or more detrimental anxiety manifes-

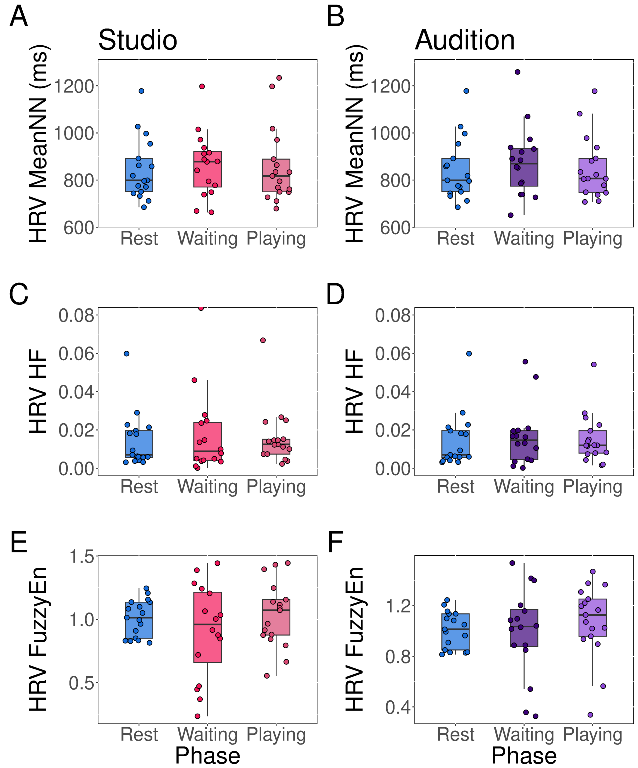

Figure 6: **No effect of anxiety induction on HRV**. **A-B**. Comparison of MeanNN, denoting the mean R-R interval during Rest, Waiting, and Playing phases in Studio and Audition settings. The Waiting period corresponds to the VR exposure, prior to performance (Playing). Boxplot and individual participant values. **C-D**. Same as A-B but for high-frequency HRV metrics. **E-F**. Same as A-B but for Fuzzy entropy. No significant changes in HRV metrics between VR conditions were observed ($P > 0.05$; Waiting and Playing HRV values were normalized with Rest values prior to analysis).

tations. Our findings suggest that future VR-based MPA research could benefit from combining HRV metrics with other physiological measures, such as cardiac output, to more accurately distinguish between challenge and threat perceptions in performance settings [17], thereby providing a clearer assessment of the effect of MPA on cardiac physiology alongside performance changes.

Further, as noted in section 4.5, arriving at the lab can temporarily elevate anxiety and arousal, so the standard practice is to record resting ECG for 5 minutes to allow participants to settle [36]. Future studies should consider recording resting ECG earlier, before exposure to melody materials, to capture a more accurate baseline.

Limitations of our study include the use of VR instead of XR, which participants commented on in relation to staying immersed during their performance. While we considered the feasibility of conducting performances using pass-through technology to integrate real-world elements into the VR environment, this would have likely caused alignment issues due to the limitations of the technology available at the time. With recent advancements, future work should enable participants to play a real-world piano while wearing the HMD, similar to [11]. The remaining challenge lies in developing technical and scenario frameworks that seamlessly integrate computer programs running an experimental paradigm to record MIDI and physiological data, ensuring consistent and synchronized capture of performance and physiological metrics across participants.

Additionally, the experimenter was not blinded to the VR condition, as they operated the software and monitored the VR content, but bias was minimized through the use of scripted instructions, identical for both VR settings, which detailed the procedural timeline. Furthermore, while participant bias cannot be entirely ruled out, particularly for subjective anxiety ratings, it is unlikely to have influenced performance variables, as participants had no knowledge of expected changes. Moreover, the absence of systematic changes in cognitive anxiety and the improvement in performance accuracy in the Audition VR condition suggest that any potential bias was minimal and not aligned with implicit expectations.

When evaluating the effectiveness of our VR environment design, participant feedback highlighted a clear distinction between the intended emotions elicited by each setting: unease in the Audition and calmness in the Studio. Spatial audio enhancements, particularly the selection of background and atmospheric audio, played a crucial role in reinforcing these emotional tones, specially in the Studio condition. The environments were deemed plausible as no feedback indicated that any elements felt out of place regarding the scenario, placements, or interior design. However, some participants expressed discord concerning the 3D avatars, which gave a game-like feel and detracted from the perceived realism of the VR environments. This feedback suggests that incorporating more photo-realistic avatars could enhance the experience [14].

6 Conclusion

Combining a VR design to induce MPA with a controlled within-subject experimental approach to assess performance, physiology, and anxiety ratings, our study demonstrated that VR is an effective tool for inducing MPA in musicians, as supported by previous research [5, 11, 30]. Moreover, our study showed an influence of VR-induced anxiety on performance along specific dimensions, pointing to an invigoration of performance and improvements in error rate over time. This suggests that MPA induced through VR can trigger adaptive, beneficial effects. The physiological measures using HRV metrics were similar between VR conditions, highlighting the need for alternative cardiac physiology metrics to distinguish between adaptive and detrimental effects of MPA. Overall, this study provides a framework for future controlled experimental studies of MPA in VR, and for intervention applications to mitigate MPA.

Our integrative work enhances the understanding of MPA, and provides recommendations into the application of VR to extend MPA research in controlled lab settings with musicians. This study also offers valuable insights for the industry and those interested in using VR for MPA training. The findings could be relevant to applications that involve simulated public performance settings in the presence of evaluators, which could be expanded by providing real-time performance analysis and feedback. In the future, we plan to improve our methods by conducting immersive performance experiments that leverage mixed reality, thereby eliminating the need for HMD removal. A primary focus will be ensuring comfort and safety during prolonged HMD. We aim to incorporate higher fidelity humanoid avatars, raise performance stakes, and utilize mobile technology to record EEG alongside additional physiological metrics in open settings like larger studios without physical constraints. Future work should validate the VR-induced effects of MPA on performance with a real-stage performance. If the effects are similar (targeting the same variables, even if real stage performance may lead to larger effects), then VR would be validated as an at-home, lab-based alternative to conduct research on MPA or to develop interventions.

Acknowledgments

The authors thank Oliver Durcan (Goldsmiths University of London) for support with the sound design and Jenny Halseid (Goldsmiths University of London) for the original design of the procedure timeline figure. This work was partly supported by the Strategic Research Funding of Goldsmiths University of London (MHR).

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