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VIRTUAL REALITY FOR PERFORMANCE PREPARATION

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ABSTRACT

Singers often encounter difficulties when transitioning from the acoustics of rehearsal spaces to those of performance venues. Can this challenge be addressed by rehearsing in a Virtual Reality (VR) simulation of the performance venue? This study evaluated the effects of VR training on four vocal parameters—vibrato extent, vibrato rate, quality ratio, and vibrato jitter—and measured singer perceptions via an Acoustic Perception Survey (APS). Nine non-voice major university students were randomly assigned to experimental (VR) or control groups. Both groups received equal preparation time for a song of their choice, which they performed in a chamber recital hall. The experimental group rehearsed using a VR replication of the venue during three voice lessons, while the control group rehearsed solely in a traditional voice studio. Singers in the VR group showed improved adaptation to the recital venue's acoustics. Additionally, the VR replication was perceived to be more supportive than the traditional studio. These findings suggest that VR-based rehearsal could help singers better prepare for unfamiliar performance venues, improving vocal outcomes and reducing anxiety. VR offers a promising tool for replicating diverse acoustic environments in the practice setting.

Keywords: *virtual reality, singing, performance anxiety, room acoustics, perception*

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1. INTRODUCTION

In the performing arts, singers and musicians have often shared anecdotal accounts of how their perceptions are influenced by the different venues in which they perform. Research has shown that both instrumentalists [1-2] and singers adjust their tone production based on the acoustic feedback from the performance space [2-6]. Some studies have examined the impact of virtually simulated acoustics on vocal production [2, 5], but these studies did not include matching visual input, which has been shown to also affect a performer's perception and production [7-9]. Indeed, a singer's performance is shaped by numerous factors, including their perception of the acoustics, the visual aesthetics of the venue, and the actual acoustic properties of the space.

This creates a challenge, as singers often rehearse in environments that are much smaller and less resonant than the performance venue, leading to a significant contrast in the acoustic feedback. This discrepancy can result in subconscious adjustments to vocal technique and heightened anxiety due to unfamiliarity with the performance space, including both its auditory and visual characteristics.

Virtual reality (VR) has the potential to address this issue in performance preparation. By using VR, singers can rehearse in both the acoustic and visual environment of the performance venue without needing to be physically present in the space.

This study aims to assess the effectiveness of VR as a pedagogical tool for singers, specifically in addressing the challenges of limited access to performance venues. Recent research has shown that virtual replicas of performance venues can elicit similar vocal responses from singers as actual performance environments [9]. This suggests that VR-based applications could be developed not only to assist

singers but also to support other performers in preparing for live performances.
The primary objective of this study is to explore how VR can increase a singer's familiarity with a performance venue. The study gathered data to answer the following research question: *How did singer vocal production and perception in the Performance compare to that in the Rehearsal Without VR and the Rehearsal With VR?*

2. EXPERIMENTAL METHOD

2.1 Participants

The use of human subjects for this research was approved by the Office for the Protection of Research Subjects at the University of Illinois Urbana-Champaign (IRB24-1182). Ten non-voice major singers volunteered to take part in the experiment and were randomly divided into an experimental group and a control group. One singer in the experimental group, however, was unable to complete the final performance. The group assignment, age, gender, and voice type of the remaining nine singers are reported in **Tab. 1**. None of the participants had previously sung in the Smith Memorial Room, the recital venue for the experiment.

Table 1. Characteristics of participants with group, age, gender, voice type, and years of voice training.

ID	Group	Age	Gender	Voice Type	Years of training
1	Control	22	Female	Soprano	2
2	Control	21	Female	Soprano	6
3	Control	23	Male	Tenor	1
4	Control	25	Male	Baritone	1
5	Control	27	Female	Mezzo-soprano	6
6	Experimental	20	Female	Mezzo-soprano	7
7	Experimental	21	Female	Soprano	4
8	Experimental	21	Male	Baritone	1
10	Experimental	20	Female	Soprano	1

2.2 Room Descriptions

The two rooms used for this study are housed within the Tina Weedon Smith Memorial Hall on the University of Illinois Urbana-Champaign campus. The Smith Memorial Room (SMR), the performance venue, is a medium-sized venue modeled after a baroque drawing room with marble floors and columns, plaster walls, three crystal chandeliers, and a large rug covering most of the floor. It seats fifty audience members and is used for many smaller recitals and chamber performances. Rehearsals With and Without VR took place in Room 342, a small windowless teaching studio with an upright piano placed in the middle of the room perpendicular to the wall.
The SMR was recreated both visually and acoustically to provide an immersive VR rehearsal experience. Singers used a Meta Quest 3 VR headset for the visual stimulus, paired with open-backed Sennheiser HD650 headphones for audio. The visuals were 360° photos of the rooms taken from the singer's stage perspective using an Insta 360 X3 camera.
To assess the room acoustics, impulse responses (IRs) were recorded with a BAS006 impulsive sound source and a calibrated NTi Audio M2211 microphone, using an XL2 audio and acoustic analyzer. Measurements were taken from various locations, with the sound source positioned where a performer would stand. Key acoustic parameters—reverberation time (RT), early decay time (EDT), and clarity (C80)—were determined using Aurora [10], a plugin for Audacity software. These parameters were averaged over the 500 Hz and 1 kHz octave bands, following ISO 3382–1 standards [11]. Acoustic characteristics for each room are summarized in **Tab. 2**.

Table 2. Reverberation time (T_{30}), clarity (C_{80}), and early decay time (EDT), measured with an impulsive source located in the singers' position (front and center) of each room, and the receiver in different audience locations. All parameters were averaged over the 500 Hz and the 1 kHz octave bands. The table lists the average, the minimum, and the maximum values measured in the audience. The volume and the occupancy (i.e., number of seats) are also included.

Room	Volume (m^3)	Occupancy	# of measurement points	T_{30} (s)	C_{80} (dB)	EDT (s)
SMR	400	56	9	1.04 (1.07-1.11)	2.00 (0.65-3.45)	0.98 (1.09-1.18)
Rm 342	17.3	2	1	0.23 (0.19-0.27)	29.72 (27.52-31.91)	0.06 (0.06-0.07)

2.3 Auralization: Equipment and Procedures

Auralization is the process of simulating room acoustics to provide a binaural listening experience from a specific position within a modeled space [12]. To create an auralization, it's crucial to replicate how a singer perceives their voice in a performance venue, which is influenced by several factors:

1. **Head diffraction** – how sound travels from the singer's mouth, around their head, and to their ears [13].
2. **Room impulse response (IR)** – how the room reacts to a brief, high-intensity sound [14].
3. **Head-related transfer function (HRTF)** – how an individual's head, ears, and torso affect how sound waves reach the eardrums from different directions.

To simulate the vocal experience, IRs were recorded capturing the sound path from the mouth to the ears of a reference head-and-torso simulator (HATS) [15]. These IRs were processed with real-time convolution plugins in Reaper software (Cockos, Rosendale, NY) and delivered to singers through open-back headphones.

2.4 Protocol

During Week One of the study, the singers were introduced to the Acoustic Perception Survey (APS) and allowed time to listen to the room's acoustics before responding at the end of the lesson with their perceptions of Room 342.
During Weeks Two and Three, the experimental group rehearsed with VR while the control group rehearsed without VR. In Week Four, the experimental group recorded two rehearsals of their song: once without VR and then with VR. The control group also rehearsed their song twice, but only recorded once, still without VR. After the lesson, members of the experimental group answered the APS about their perceptions of the VR of SMR.
The performance was held in the SMR with a randomized performance order. Afterwards, all participants completed the APS survey about the SMR. In Week Six after the recital, members of the control group were allowed one Rehearsal with VR, and then they responded to the APS survey about their perceptions of the VR of SMR.
The survey and its analytical approach used in this study follow Redman et al. [16], and the acoustic parameters and subsequent analyses follow Bottalico et al [3].

2.5 Statistical Analysis

Statistical analyses of the objective voice parameters were conducted using linear mixed models (LMM). These analyses were performed with R software (version 3.6.0) and the lme4 package (version 1.1-10). Different models were built for each response variable—vibrato extent (V_{ext}), vibrato rate (V_{rate}), quality ratio (QR), and vibrato jitter (V_{jitter}). The models were computed for each of the four voice parameters with three sensory conditions (Performance, Rehearsal Without VR and Rehearsal With VR) as fixed effects and participant ID as a random effect.
The analysis of the APS was divided into two phases. In the first phase, the objective was to identify the set of significant affective impressions in the overall evaluation of the sensory conditions. The second phase used LMM to determine the relationship between sensory conditions and participants' subjective impressions.

3. RESULTS

3.1 Effect of Sensory Conditions on Voice Production

Differences in vibrato extent (V_{ext}) between performance and rehearsal conditions, with and without VR, were analyzed for both the control and experimental groups. Linear mixed-effects (LME) models were applied, with three sensory conditions (Performance, Rehearsal Without VR and Rehearsal With VR) as fixed effects and participant ID as a random effect.
For the control group, the fixed effect of sensory condition was not significant, indicating that V_{ext} remained relatively stable between the Performance and the two Rehearsal conditions. V_{ext} was larger in the Rehearsal Without VR condition compared to the Performance, but the difference was not statistically significant. Similarly, the Rehearsal With VR after the performance showed a smaller V_{ext} but the effect was not significant. The estimate of *SD* for random effect was 2.70 for participant ID, while the residual *SD* was 18.47, indicating moderate variability across observations.
For the experimental group, the mean V_{ext} in the Performance was larger at 54.32 cents compared to the control group (17.10 cents). V_{ext} in the Rehearsal Without VR was significantly smaller than in the Performance (Estimate = -35.14, p = 0.047). However, V_{ext} in the Rehearsal With VR was not significantly different from that of the Performance. Random effects for V_{ext} in the experimental group exhibited higher variability compared to the control group, with a *SD* of 22.45 for participant ID and a residual *SD* of 58.18.
Fig. 1 shows the mean V_{ext} (in cents) for the two groups (control and experimental) across different sensory conditions, with error bars representing the standard error. The x-axis represents the three sensory conditions, while the y-axis shows the mean vibrato extent (Vext_m). Each point on the line indicates the mean V_{ext} for each condition, with error bars capturing the variability in the data. The figure shows that for the experimental group, V_{ext} was significantly smaller in the Rehearsal Without VR than in

the Performance. Meanwhile, the control group showed more consistent results across all conditions.

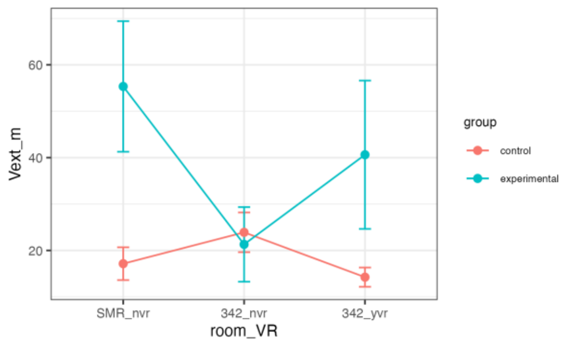

Figure 1. Plot showing the mean vibrato extent (Vext_mean_cent) for the two groups across three sensory conditions. “SMR_nvr” corresponds to the Performance while “342_nvr” and “342_yvr” correspond to the Rehearsal Without and With VR, respectively. Error bars indicate the standard error.

Differences in vibrato rate (V_{rate}) between performance and rehearsal conditions, with and without VR, were analyzed for both the control and experimental groups. Linear mixed-effects (LME) models were applied, with three sensory conditions (Performance, Rehearsal With VR and Rehearsal Without VR) as fixed effects and participant ID as a random effect.

For the control group, the mean V_{rate} in the performance was 6.05 Hz. V_{rate} in neither the Rehearsal With VR nor the Rehearsal Without VR was significantly different from the Performance. Random effects showed a residual *SD* of 0.62, with negligible variance in the *SD* for participant ID (*SD* = 0), suggesting relatively stable V_{rate} measurements across participants.

In the experimental group, the mean V_{rate} was higher at 6.65 Hz. However, V_{rate} in neither the Rehearsal With VR nor the Rehearsal Without VR was significantly different from the Performance. Random effects for the revealed a higher residual *SD* of 0.93, but like the control group, there was negligible variance in the *SD* for participant ID (*SD* = 0), indicating consistency in participant-level V_{rate}.

Fig. 2 shows the mean V_{rate} (Hz) across different sensory conditions, with error bars representing the standard error. The x-axis represents the three sensory conditions, while the y-axis shows the mean V_{rate}. Each point on the line indicates the mean V_{rate} for each condition, with error bars capturing the variability in the data.

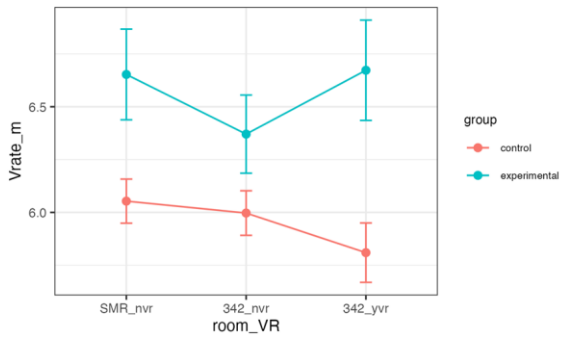

Figure 2. Plot showing the mean vibrato rate (in Hertz) across three sensory conditions. “SMR_nvr” corresponds to the Performance while “342_nvr” and “342_yvr” correspond to the Rehearsal Without and With VR, respectively. Error bars indicate the standard error.

Differences in quality ratio (QR) between performance and rehearsal conditions, with and without VR, were analyzed for both the control and experimental groups. Linear mixed-effects (LME) models were applied, with three sensory conditions (Performance, Rehearsal With VR and Rehearsal Without VR) as fixed effects and participant ID as a random effect.

For the control group, the fixed effect of sensory condition was not significant, indicating that QR remained relatively stable between the Performance and the Rehearsal Without VR as well as the Rehearsal With VR. The estimate of *SD* for random effect was 3.78 for participant ID, while the residual *SD* was 5.40.

In the experimental group, the Performance resulted in a QR of 20.57. QR in the Rehearsal Without VR was significantly lower than in the Performance (Estimate = −3.68, *p* = 0.013). However, the Rehearsal With VR did not significantly differ from the performance. The estimate of *SD* for random effect was 2.5 for participant ID, while the residual *SD* was 4.97.

Fig. 3 shows the mean QR across different sensory conditions, with error bars representing the standard error. The x-axis represents the three sensory conditions, while the y-axis shows the mean QR. Each point on the line indicates the mean QR for each condition, with error bars capturing the variability in the data. Similar to V_{rate}, both groups showed a reduction in QR when they recorded in the condition different from what they had previously rehearsed.

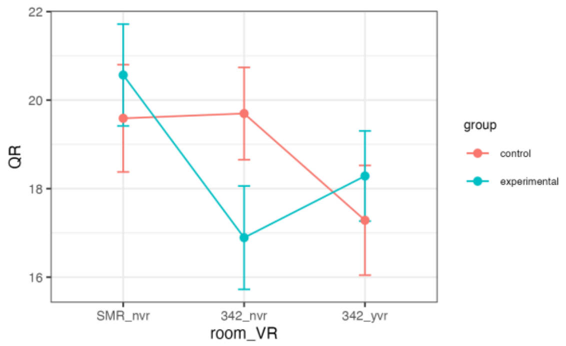

Figure 3. Plot showing the mean Quality Ratio (QR) in dB across three sensory conditions. "SMR_nvr" corresponds to the Performance while "342_nvr" and "342_yvr" correspond to the Rehearsal Without and With VR, respectively. Error bars indicate the standard error.

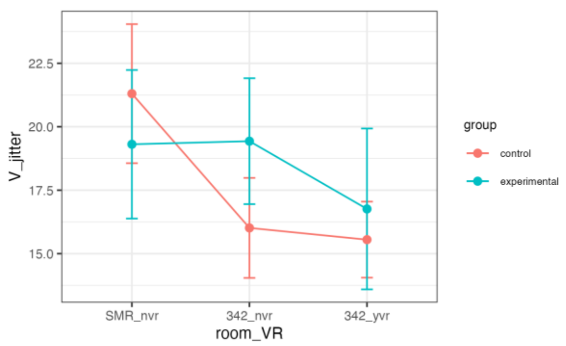

Figure 4. Plot showing the mean Vibrato Jitter (in %) across three sensory conditions. "SMR_nvr" corresponds to the Performance while "342_nvr" and "342_yvr" correspond to the Rehearsal Without and With VR, respectively. Error bars indicate the standard error.

Differences in vibrato jitter (V_{jitter}) between performance and rehearsal conditions, with and without VR, were analyzed for both the control and experimental groups. Linear mixed-effects (LME) models were applied, with three sensory conditions (Performance, Rehearsal With VR and Rehearsal Without VR) as fixed effects and participant ID as a random effect.
For the control group, the estimate of V_{jitter} was 21.31% in the Performance. V_{jitter} in the Performance was significantly higher than in the Rehearsal With VR (Estimate = -5.84, p = 0.048), while V_{jitter} in the Rehearsal Without VR was approaching statistical significance (Estimate = -5.20, p = 0.083).
For the experimental group, the estimate of V_{jitter} in the Performance was also 21.31%, showing a similar baseline V_{jitter} as the control group. However, V_{jitter} was not significantly different from the Performance in either Rehearsal condition, With or Without VR.
Fig. 4 shows the mean vibrato jitter (in %) across different sensory conditions, with error bars representing the standard error. The x-axis represents the three sensory conditions, while the y-axis shows the mean V_{jitter}. Each point on the line indicates the mean V_{jitter} for each condition, with error bars capturing the variability in the data. The control group exhibited a significant increase in V_{jitter} during the Performance compared to the Rehearsal With VR, as well as a near-significant increase compared to the Rehearsal Without VR. In contrast, the experimental group showed no significant differences in V_{jitter} between the Performance and either rehearsal condition.

3.2 Effect of Sensory Conditions on Acoustic Perception

The singers' perception was analyzed as in Redman et al. [16]. A factor analysis was performed using Ordinary Least Squares (OLS) to find the minimum residual (minres) solution. The cumulative variance explained by the first axis was 94 %. The contribution of the original items to the axis was analyzed to determine the concept associated with it, thereby obtaining the following factor: ***Singing Voice Supportiveness***, the assessment of the voice support provided by the room combined with the overall assessment from the singers' perspective.
The results of the linear mixed-effects (LME) model, fit using restricted maximum likelihood (REML), assess whether different Sensory Conditions differed in *Singing Voice Supportiveness*.
The baseline condition of the SMR had a significant intercept (Estimate = 10.29, p < 0.001), indicating a high level of *Singing Voice Supportiveness*. The VR of SMR condition (342_yvr) was significantly different from the SMR, with a lower *Singing Voice Supportiveness* score (Estimate = −1.77, p = 0.005). Room 342 (342_nvr) was also significantly different from the SMR, showing an even lower *Singing Voice Supportiveness* score (Estimate = −3.26, p < 0.001). **Fig. 5** shows the mean *Singing Voice Supportiveness* across different sensory conditions, with error bars representing the standard error.

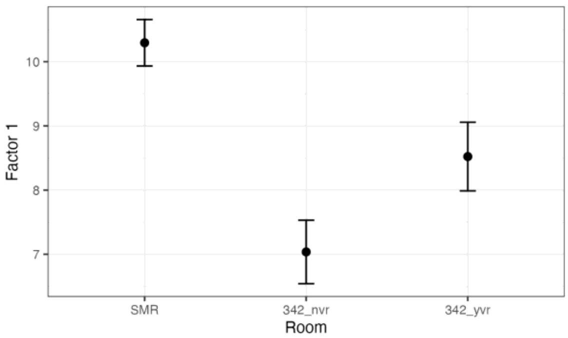

Figure 5. Mean of the *Singing Voice Supportiveness* (Factor 1) across three sensory conditions. Error bars indicate the standard error.

4. DISCUSSION & CONCLUSIONS

The aim of the present study was to determine the effect of Virtual Reality (VR) Training on performance outcomes in terms of voice production and acoustic perception. The experimental group received three weeks of VR Training leading up to a recital performance, while the control group prepared for three weeks under normal voice studio conditions and only rehearsed with VR once after the recital. Voice production in the Performance, Rehearsal With VR, and Rehearsal Without VR was measured in terms of four objective voice parameters: vibrato extent (V_{ext}), vibrato rate (V_{rate}), quality ratio (QR), and vibrato jitter (V_{jitter}). Participants rated their acoustic perceptions of the three environments (SMR, the VR Replication of SMR, and Room 342) by answering the Acoustic Perception Survey. A factorial analysis of the survey items resulted in one subjective category, *Singing Voice Supportiveness*, which explained 94% of the information in their answers.

The experimental group showed a higher V_{ext} during the performance than the control group, suggesting that VR training led to a more developed vibrato. The control group did not exhibit significant differences in V_{ext} between the performance and rehearsal conditions. However, the experimental group demonstrated a notable increase in V_{ext} during both the Performance and the Rehearsal With VR compared to the Rehearsal Without VR.

Both groups showed no significant differences in V_{rate} between the performance and rehearsal conditions. This finding is consistent with previous studies indicating that V_{rate} tends to be more stable over time within individual singers and is less affected by acoustic factors compared to V_{ext} [3, 17-18].

The control group showed no significant differences in QR between the Performance and either rehearsal condition. In contrast, the experimental group exhibited a significantly higher QR during the Performance compared to the Rehearsal Without VR.

The control group showed a significantly higher V_{jitter} during the Performance compared to the Rehearsal With VR, with a trend approaching significance compared to the Rehearsal Without VR. In contrast, the experimental group exhibited no significant differences in V_{jitter} between the Performance and either rehearsal condition.

Each participant evaluated their acoustic perceptions of three spaces: the SMR, its VR replication, and Room 342. Factorial analysis revealed that 94% of the variance was accounted for by a single factor: *Singing Voice Supportiveness*. In general, the SMR was rated as the most acoustically supportive, followed by the VR simulation of SMR, while Room 342 received the lowest ratings. These results indicate that while VR can mimic certain acoustic properties of a real venue, it does not fully replicate the supportive qualities of the actual room.

Both groups showed similar V_{ext} in the performance, reflecting the rehearsal conditions they had practiced most. The experimental group demonstrated higher V_{ext} in both the Performance and Rehearsal With VR compared to the control group across all conditions. This suggests that the experimental group had more time to acclimate to the acoustics of the SMR, carrying this adjustment into their performance. In contrast, the control group, with limited exposure to VR, maintained their V_{ext} from consistent Rehearsal Without VR.

The experimental group showed a lower quality ratio (QR) in Rehearsal Without VR, possibly indicating improved tone clarity or an upward adjustment of their harmonic spectrum in response to reduced external auditory feedback, as suggested by Ternström [6]. Conversely, the control group, with no prior exposure to the performance environment, had to process unfamiliar stimuli during the performance, likely contributing to the increased V_{jitter} observed compared to their rehearsal sessions.

Overall, the experimental group's VR training likely facilitated better adaptation to the performance venue, leading to more stable vocal production, while the control group struggled with the unfamiliar acoustics, resulting in higher V_{jitter}. This study also offers valuable insights into singers' perceptions of different acoustic environments, emphasizing that real-world spaces provide the most support, while VR serves as a useful, albeit imperfect, alternative. Future studies should focus on refining VR simulations to more accurately reflect the acoustic characteristics of live performance venues.

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