# Minimally Disruptive Auditory Cues: Their Impact on Visual Performance in Virtual Reality - Supplementary Material

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## Abstract

Virtual Reality (VR) has the potential to become a revolutionary technology with a significant impact on our daily lives. In VR, the user can actively interact with the computer-generated content via their own body and perceive the virtual environment through their senses, as opposed to the more passive experience delivered by traditional media. This immersive experience accompanied by the feeling of presence elicits a realistic behavioral response, so much so that VR is becoming a sandbox to study human perception and behavior. In this work, we leverage the full control of audiovisual cues provided by VR to study an audiovisual suppression effect (ASE) where auditory stimuli degrade visual performance. In particular, we study if barely audible sounds (in the range of the limits of hearing frequencies) can still trigger the ASE while participants are experiencing high cognitive loads. Our results show that the ASE is robust to variations in frequency, volume and cognitive load. Using more subtle auditory cues means that this effect could be used in real applications, from entertaining to VR techniques like redirected walking.

## Keywords

Virtual Reality, Multimodality, Human Perception, Suppression Effect

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This Supplementary Material document contains additional details for the following sections:

- (S1) Frequency Test: Additional details on the frequency test performed by the participants
- (S2) User study surveys: Demographic (S2.1), post-test (S2.2) and sickness (S2.3) questionnaires

## S1. Frequency Test

As we have already mentioned, the goal of this work is to extend the previous work by Malpica et al. by using more subtle sounds to trigger the ASE. In this sense, our idea is to use pure frequency tones located at the limits of the participants' hearing range to degrade visual performance in both detection and recognition tasks.

Since the hearing range is different for each participant, it is necessary to calibrate the frequency limits before each experiment. Therefore, before the experiment, participants performed a frequency test in quiet, without any background noise, to obtain these frequency values.

The VE dedicated to this frequency test is only composed of an empty space with a signboard located in front of the user, where the frequency value being played is displayed as information to the experimenter, as well as the upper and lower frequency values recorded. There is also an audio source collocated with the user that continuously plays a frequency tone. At the start, the frequency value is 0 Hz and the experimenter increases it with batches of 10 Hz or 100 Hz depending on the sensitivity associated to the hearing range area. These batches were only 50Hz for the pilot study and were fine-tuned for the main experiment.

The participants are told to notify the experimenter whenever they start to hear a tone, indicating the frequency value associated with the lower limit. Then, the frequency keeps increasing until the participant does not hear the tone anymore. At that moment, the participant notifies again the experimenter, indicating the upper limit.

Two frequency values are considered as audio sources in the pilot experiment. The results obtained from this frequency test can be found in Table 1. In this table, we can find the lower (F1) and upper (F2) frequency limits. Regarding the lower limit, the mean frequency recorded was 191 Hz with a standard deviation of ± 51 Hz. On the other hand, the mean frequency was 13088 Hz with a standard deviation of ± 1825 Hz for the upper limit. We can notice how there is a clear difference between the reported standard deviations. Therefore, frequency batches were properly tuned for the frequency experiments attached to the main study.

Regarding the main experiment, and once both frequency values (high and low-frequency limits) are obtained, intervals of 40Hz and 200Hz are additionally used for lower and upper values respectively to get new near-limit values. Using these intervals, we get other values just above and below the limits, setting values inside and outside the hearing range, which are used as auditory stimuli in the main experiment.

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Consequently, each limit has three frequency values associated: The proper frequency limit and two frequencies near that limit, inside and outside the audible range. The difference in these intervals' magnitude is related to the human sensitivity throughout the hearing range. The frequencies used daily (human voices, musical notes...etc.) are closer to the lower limit so we have a higher sensitivity in that region due to physiological reasons [1]. As a result, we need to use a more extended interval for the upper limit, where sensitivity is notoriously lower, so the user can notice significant changes when perceiving the pure frequency tone.

All these frequency values, six in total, are used as audio sources in the main experiment. The results obtained from this frequency test can be found in Table 2. In this table, we can find the lower (F1) and upper (F2) frequency limits, as well as the near values inside (F1U and F2D) and outside (F1D and F2U) the hearing range respectively. Regarding the lower limit, the mean frequency recorded was 64 Hz with a standard deviation of ±27 Hz. On the other hand, the mean frequency was 15295 Hz with a standard deviation of ±1463 Hz for the upper limit. As we observed with the results obtained for the pilot study, different orders on the standard deviations support the different range intervals used for each lower and upper-frequency limit values inside and outside the hearing range.

| ID | Lower Limit (F1) | Upper Limit (F2) |
|---|---|---|
| 01 | 200 | 13500 |
| 02 | 200 | 13300 |
| 03 | 150 | 11800 |
| 04 | 120 | 12650 |
| 05 | 150 | 13200 |
| 06 | 100 | 15500 |
| 07 | 200 | 14600 |
| 08 | 200 | 10200 |
| 09 | 200 | 13000 |
| 10 | 100 | 15700 |
| 11 | 200 | 13000 |
| 12 | 200 | 14200 |
| 13 | 300 | 14800 |
| 14 | 200 | 12000 |
| 15 | 200 | 15000 |
| 16 | 200 | 14300 |
| 17 | 300 | 13000 |
| 18 | 200 | 12700 |
| 19 | 200 | 8300 |
| 20 | 200 | 11000 |

**Table 1: Frequency test results obtained in the pilot experiment. Both the lower and upper bounds of the hearing range per participant can be found. All values are measured in Hertz (Hz).**

| ID | F1 | F1D | F1U | F2 | F2D | F2U |
|---|---|---|---|---|---|---|
| 21 | 40 | 20 | 80 | 13900 | 13700 | 14100 |
| 22 | 60 | 20 | 100 | 15300 | 15100 | 15500 |
| 23 | 60 | 20 | 100 | 17900 | 17700 | 18100 |
| 24 | 60 | 20 | 100 | 14000 | 13800 | 14200 |
| 25 | 100 | 60 | 120 | 14800 | 14600 | 15000 |
| 26 | 80 | 40 | 100 | 12800 | 12600 | 13000 |
| 27 | 60 | 20 | 100 | 15700 | 15500 | 15900 |
| 28 | 60 | 20 | 100 | 17200 | 17000 | 17400 |
| 29 | 60 | 20 | 100 | 15200 | 15000 | 15400 |
| 30 | 100 | 60 | 140 | 16600 | 16400 | 16800 |
| 31 | 60 | 20 | 100 | 13000 | 12800 | 13200 |
| 32 | 60 | 20 | 100 | 15400 | 15200 | 15600 |
| 33 | 60 | 20 | 100 | 15000 | 14800 | 15200 |
| 34 | 60 | 20 | 100 | 15900 | 15700 | 16100 |
| 35 | 160 | 120 | 200 | 15400 | 15200 | 15600 |
| 36 | 80 | 40 | 120 | 12900 | 12700 | 13100 |
| 37 | 60 | 20 | 100 | 17600 | 17400 | 17800 |
| 38 | 40 | 20 | 80 | 16500 | 16300 | 16700 |
| 39 | 40 | 20 | 80 | 15500 | 15300 | 15700 |
| 40 | 60 | 20 | 100 | 15300 | 15100 | 15500 |

**Table 2: Main Experiment Participants: Frequency Test Results Both the lower and upper bounds of the hearing range per participant can be found, as well as the respective close values inside and outside the hearing range. All values are measured in Hertz (Hz).**

## S2. User Study Surveys

In addition to the demographic survey (S2.1) performed before the main experiment, participants also filled out debriefing surveys (S2.2) as well as sickness questionnaires (S2.3). The questions asked in these surveys can be found at the end of this document.

Regarding the debriefing review, most of the participants (16 out of 20) reported not having any issues when wearing the HMD. Those who had any issues, mentioned blurry vision probably related to bad positioning or calibration. Almost all of the participants (18 out of 20) found it easy to understand and perform the experiment whereas it was generally difficult (16 out of 20) to distinguish the visual targets due to the targets' small size and similar shapes. Regarding auditory stimuli, 16 participants claimed that they were easy to detect while 17 participants were not able to predict when any stimuli were going to spawn. Lastly, the sense of immersion and presence was achieved, participants reported feeling the virtual environment as the reality itself and also the feeling of truly being there.

A sickness questionnaire was also fulfilled by participants twice, before and after performing the experiment. The participants' mood and physical state were asked at the beginning and then compared with how participants felt at the end. According to this, participants did not experience any side effects or drawbacks when performing or after the experiment.

## S2.1 Demographic Survey

**E1. What is the experiment about?**

I agree to participate in this research experiment. I understand the purpose and nature of this study and I am participating voluntarily. I understand that I may withdraw from the experiment at any time without any kind of penalty or consequence. I consent to the use of the data generated from this questionnaire in the researcher's publications on this topic. Any personal information obtained throughout this study will remain confidential and will be released only with your specific permission.

☐ *I agree*

**E2. Session recording acceptance**

I authorize recording this session for further study

☐ *I agree*

**Q1. Subject anonymous ID**

_____

**Q2. Age**

_____

**Q3. Gender**

☐ *Male* ☐ *Female* ☐ *Rather not to say* ☐ *Other*

**Q4. Birthplace (as concrete as possible)**

☐ *Zaragoza* ☐ *Aragon* ☐ *Spain* ☐ *Other*

**Q5. Education (highest level completed)**

☐ *No formal education*
☐ *Elementary School*
☐ *High School or equivalent*
☐ *Baccalaureate Degree*
☐ *Master Degree*
☐ *Doctorate (e.g. PhD) or higher*
☐ *Other*

**Q6. Do you have any visual impairments**

☐ *Yes* ☐ *No*

**Q7. If you answered "Yes" to the previous question, please specify your condition (e.g. poor distance vision):**

_____

**Q8. If you have any visual impairments, do you have it corrected? (e.g. by wearing glasses or contact lenses)**

☐ *Yes* ☐ *No*

**Q9. Do you have any auditory impairments**

☐ *Yes* ☐ *No*

**Q10. If you answered "Yes" to the previous question, please specify your condition (e.g. age-related hearing loss):**

_____

**Q11. If you have any auditory impairments, do you have it corrected? (e.g. by wearing an ear-mounted device)**

☐ *Yes* ☐ *No*

**Q12. Do you have any characteristics that make you fall into the neurodivergent group e.g. dyslexia, autism? If so, please indicate your condition.**

_____

**Q13. If there any other information you may consider relevant for the experiment to know?**

_____

**Q14. Do you play videogames**

□ *Yes* □ *No*

**Q15. If you have answered "Yes" to the previous question, how much time do you spend daily playing video games?**

□ *Low (one hour at most)*
□ *Moderate (between one hour and three)*
□ *High (more than three hours)*

**Q16. Did you hear about virtual reality (VR) before?**

□ *Yes* □ *No*

**Q17. Have you ever used a virtual reality (VR) device before?**

□ *Yes* □ *No*

**Q18. If you have answered "Yes" to the previous question, how often?**

□ *Rarely* □ *Occasionally* □ *Daily*

**Q19. If you have ever used a VR device, please check those that apply:**

□ *I have used computer-type devices such as HTC Vive, Oculus or Play Station VR.*
□ *I have used smartphone-based devices*

**Q20. Have you ever experienced eyestrain, sickness, headache or nausea when using VR?**

□ *Yes* □ *No* □ *I have never used VR before*

## S2.2 Post-test Survey

**Q1. Subject anonymous ID**

_____

**Q2. Did you have any problem wearing and using the VR headset (HMD)?**

□ *Yes* □ *No*

**Q3. If you have answered "Yes" to the previous question, please specify what problems you encountered (e.g. size, malfunction)?**

_____

**Q4. In general, have you found it easy to perform the experiment?**

□ *Yes* □ *No*

**Q5. If you answered "No" to the previous question, please specify what kind of issues you encountered (e.g. operation, scene, comfort, procedure)**

_____

**Q6. Throughout the experiment, were you able to distinguish the visual targets easily?**

□ *Yes* □ *No*

**Q7. If you answered "No" to the previous question, please specify what made distinguishing the visual targets difficult (e.g. color, location, size, shape)**

_____

**Q8. Would you include other types of visual targets? Please check those that apply**

□ *More complex shapes*
□ *Scene objects*
□ *Videos*
□ *Other:* _____
□ *No, I would not*

**Q9. Write any comment or suggestion that you would like to point out regarding the visual targets (if any)**

_____

**Q10. Throughout the experiment, were you able to listen the audio sources easily?**

□ *Yes* □ *No*

**Q11. If you answered "No" to the previous question, please specify what made listening to the audio sources difficult (e.g. volume, location)**

_____

**Q12. Write any comment or suggestion that you would like to point out regarding the audio sources (if any)**

_____

**Q13. Throughout the experiment, were you able to predict when an audio source or a visual target would sound or spawn respectively?**

□ *Yes* □ *No*

**Q14. Please, rate your feeling of being in the virtual environment on the following scale from 1 to 5, where 5 represents a normal experience of being in a real place. I had the feeling of "being there" in the virtual environment.**

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| *Not at all* | □ | □ | □ | □ | □ | *Completely* |

**Q15. How long during the experience the virtual environment was like reality for you?**

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| *Never* | □ | □ | □ | □ | □ | *All the time* |

**Q16. Throughout the experience, which was stronger in general: the feeling of being in the virtual environment or another real place?**

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| *Virtual Environment* | □ | □ | □ | □ | □ | *Another Place* |

**Q17. When you look back on your experience, do you remember the living room space more like images you saw or a place you visited?**

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| *Images I saw* | □ | □ | □ | □ | □ | *Place I visited* |

**Q18. To improve the experiment and the user experience, please report any comment, suggestion or review you may have**

_____

## S2.3 Sickness Survey

**Q1. Subject anonymous ID**

_____

**Q2. Session**

□ *Before* □ *After*

**Q3. According to your current condition, indicate the degree of the following symptoms:**

| Symptoms | None | Mild | Moderate | Severe |
|---|---|---|---|---|
| Tiredness | □ | □ | □ | □ |
| Headache | □ | □ | □ | □ |
| Eyestrain | □ | □ | □ | □ |
| Blurry Vision | □ | □ | □ | □ |
| Dizziness | □ | □ | □ | □ |

## References

[1] B Masterton, Henry Heffner, and R Ravizza. 1969. The Evolution of Human Hearing. *The Journal of the Acoustical Society of America* 45 (05 1969), 966–85.