Effects of sound masking noise on workers' perception and performance

Qingyang Wang

A Thesis

In the Department

Of

Building, Civil and Environmental Engineering (BCEE)

Presented in Partial Fulfillment of the Requirements

For the Degree of Master of Applied Science (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

July 2024

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Qingyang Wang

Entitled: Effects of sound masking noise on workers' perception and performance

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

Dr. S. Samuel Li ______________________ Chair

Dr. Farah Hafeez ______________________ Examiner

Dr. Jong Won Ma ______________________ Examiner

Dr. Joonhee Lee ______________________ Thesis Supervisor(s)

______________________ Thesis Supervisor(s)

Approved by ______________________

Dr. Mohamed Ouf Chair of Department or Graduate Program Director

____

Mourad Debbabi Dean of Gina Cody School of Engineering and Computer Science

ABSTRACT

Effects of sound masking noise
on workers' perception and performance

Qingyang Wang

There is always a lack of separation between individual work areas in open offices, so sound insulation is poor. A cheap and effective solution to this problem may be to use sound masking technology. This study aims to explore the impact of sound masking noise on employee perception and psychology in scenarios involving two types of signal speech noise involving sound masking technology. Specifically, this study implemented background noise, speech, visual stimuli, and interactive components required in a real-time virtual reality framework. Ten participants participated in a multi-task cognitive experiment. The key metrics for evaluation include task completion rate, accuracy, NASA Task Load Index, and individual noise sensitivity scores.

The average accuracy is lower in the 50 dBA with speech condition compared to the 38 dBA with speech condition. Similarly, participants complete fewer math questions on average in the 50 dBA with speech condition compared to the 38 dBA with speech condition. The combination of higher noise levels and speech (bad signal-to-noise ratio for speech) significantly hampers task efficiency. It shows that the ten participants have different levels of sensitivity to noise or speech. People with higher noise sensitivity will experience the highest task load in noisy environments with speech. In environments with irregular noise patterns, sound masking systems may inadvertently amplify rather than mask irregular noise. This study not only observed individual differences in noise sensitivity and cognitive effects, but also highlighted the importance of individual responses to noise in managing noise exposure in the open plan offices.

Keywords: sound masking

Table of Contents

Table of Contents iv
List of Figures vi
List of Tables vii
List of Abbreviations viii
Chapter 1. Introduction 1
1.1. Background 1
1.2. Thesis Objectives 4
1.3. Study outline 5
1.4 Definition of terms 5
Chapter 2. Literature review 10
2.1. VR technology 10
2.2. Utilization of Virtual Acoustic Environments in the conduct of auditory experiments 11
2. 3 Sound masking system 15
2.3.1 Sound source level for sound masking system 15
2.3.2 Indirect Sound Masking Technology in open-plan offices 16
Chapter 3. Methodology 17
3.1. Experimental Environment 17
3.2. Sound materials 21
3.3. Experimental design and procedure 24
3.4. Ethical Considerations 29
4. Chapter four. Results and discussion 30
4.1. Measurement Results 30
4.1.1 Impact of Noise Types on Task Performance 32
4.1.2 Influence of Noise Types on Cognitive Perception. 34
4.1.3 Noise Sensitivity and Task Load Relationship 35
4.3. summary 42
5. Conclusion 44
5.1. Summary 44
5.2. Limitations 45
5.3. Future study 46

References 48
Appendix A: Sequence of Experimental Conditions..52
Appendix B: Detailed calculations employed in the VR tasks 53
Appendix C: NASA Task Load Index 58

List of Figures

Figure 1. All the environmental factors workers dissatisfied with (58) 1
Figure 2. A sound masking system is typically installed above the ceiling (36) 3
Figure 3. Soundwaves vibrate the air, sending the audio through the outer ear to the eardrum, which vibrates to send the sound information to the brain for processing (66) 6
Figure 4 . Internal anatomy of the ear (67) 9
Figure 5. integrating a framework into a VR project (25) 13
Figure 6. a conceptual overview of the illustration how to create and reproduce in a scene (31) 14
Figure 7. The exterior appearance of an open-plan office 18
Figure 8. Open Plan Office Layout Diagram 19
Figure 9. Floor plan of Open Plan Office 19
Figure 10. Planar diagram of four source positions and one receiver location 20
Figure 11. Side view diagram 20
Figure 12. Side view diagram 2 21
Figure 13. Line chart for four conditions 24
Figure 14. Task 1 (part two) 27
Figure 15. Task 2 28

List of Tables

Table 1 Description of the actual sound recording used in the experiment. 22
Table 2. Speech spectrum for all the conditions 23
Table 3.comparisons of measured and preset values 25
Table 4. Attributes of participants... 30
Table 5.Presentation of the results of the acoustic survey 30
Table 6. The following linear regression graphs depict the relationship between noise sensitivity and the NASA Task Load Index (NASA-TLX) for the four conditions. 35
Table 7: correlation calculation of four conditions.. 37
Table 8. correlation matrix for 38 dBA condition 38
Table 9. correlation matrix for 38 dBA with speech condition 39
Table 10. correlation matrix for 50 dBA condition 40
Table 11.correlation matrix for 50 dBA with speech condition 41

List of Abbreviations

Abbreviation	**Description**
SPL	Sound Pressure Level
HVAC	Heating, ventilation and air conditioning
Ltot,a	Overall A-weighted sound pressure level
Lz	unweighted octave band sound pressure level
SMS	Sound masking system
VR	Virtual reality
VA	Virtual acoustic
NASA-TLX	The NASA Task Load Index

Chapter 1. Introduction

1.1. Background

Open-plan offices are characterized by spacious rooms with rows of desks, where employees work at a close distance to each other, typically without partitions or separators. Open-plan offices offer advantages such as being cheaper and more cost-effective. Using the limited space, more employees can be fitted in a workable space and soft seating areas [1]. However, an open office environment is usually prone to noise disturbances for office workers, including the sound of colleagues talking, ringing phones, printers, etc. As stated in Figure 1, according to the findings of the Center for the Built Environment in Berkeley, California. After surveying more than 24,000 workers in over 2,000 buildings, speech privacy emerged as the most important factor causing dissatisfaction among workers across all the office layouts [2].

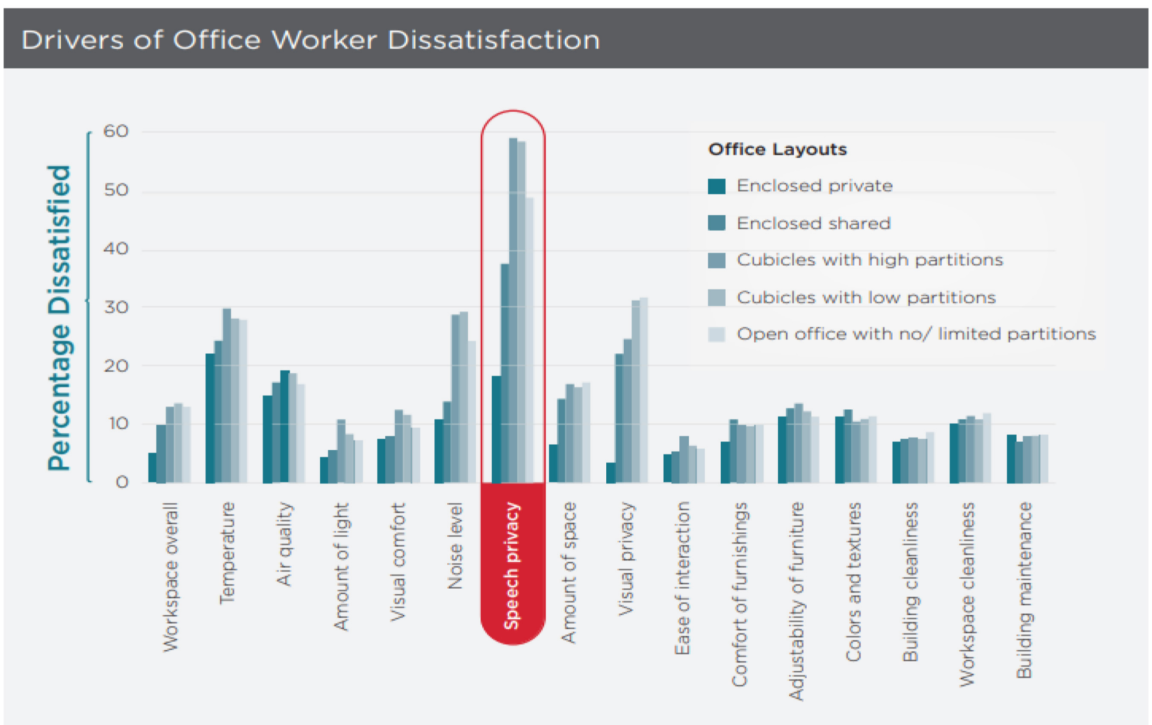


Figure 1. All the environmental factors workers dissatisfied with [2]

The presence of these noises can cause distractions, disrupt concentration, and have a negative impact on productivity. This problem is particularly prominent in modern office spaces because offices usually use hard materials like glass and concrete, which reflect sound rather than absorb it [3]. The requirement of sustainable office building interior design is thermal comfort, satisfaction, health [4]. Professionals in the field of acoustics often face significant challenges when dealing with these kinds of particular problems. There is an urgent need among professionals to develop a comprehensive office room design that addresses acoustics specifically.

In the pursuit of an acoustically comfortable environment, completely eliminating all the noise in the office is an impractical and difficult-to-achieve task. Necessary noise sources require appropriate control measures through effective and good acoustic management [5]. One of the effective ways to solve this problem is sound masking technology. Sound masking is a form of acoustic masking achieved by adding specific background sounds to the environment [6]. Sound masking generators are typically connected to a traditional public address amplifier system and distributed around the room via ceiling speakers to ensure that sound masking is evenly distributed throughout the controlled environment [7]. Sound transmitters are distributed around the room you want to screen and broadcast a specially designed signal. The reason for this is to keep background noise at a consistent and moderate level, thereby reducing the likelihood of worker distraction [8]. Sound masking must be quiet, soft, and natural. The masking effect should appear natural to people working in the area [9].

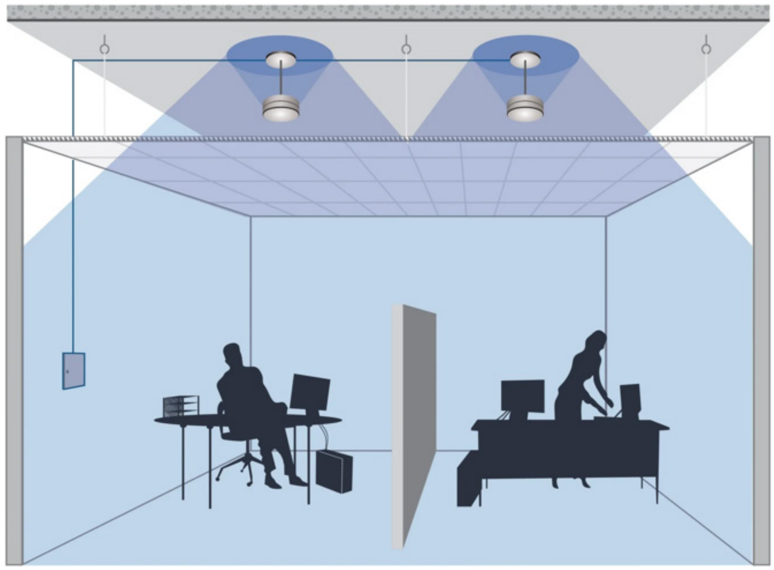


Figure 2. A sound masking system is typically installed above the ceiling [8] [10]

In office environments, sound masking technology plays a significant role. Sound masking technology helps dilute distracting noise and conversation in background noise by drowning out noise that targets the same frequency as human speech [10]. This technology not only helps address speech privacy concerns but also reduces potential distractions for employees in the workplace, which can improve work efficiency and office comfort. By introducing moderate background noise, the working environment was successfully improved. Sound masking technology plays a key role in drowning out noise distractions and the impact of surrounding conversations. This not only enables employees to protect private conversations and avoid being interrupted by other colleagues, but also allows employees to focus more on the task at hand, creating a relatively quiet and focused work environment, thereby significantly improving work efficiency [6]. While introducing less prominent sounds into the office may impact the intelligibility of human speech, it can also help improve speech privacy and reduce distracting noise. Sound masking does not completely eliminate disruptive noise, but blends it with other sounds in innovative ways [3]. When you don't understand what someone is saying, their words are less distracting—in fact, you may not even be aware of what they are saying [11].

Sound masking is an effective and cost-effective engineering technique that can reduce the cost of company construction by introducing specific sounds to reduce the need for sound-absorbing and soundproofing materials. This solution effectively addresses one of the most common complaints among modern office workers – speech privacy [3]. This specialized design aims to enhance employee performance and productivity. The open pace office environment is a complex listening environment with varying levels of background noise and reverberation time. Currently, there is still potential for further research and development in understanding the acoustic aspects of open office design. However, this raises a key question: Is sound masking the perfect solution to this dilemma? How does sound masking noise affect employee perception and psychological endurance in demanding jobs in the open plan office? Meanwhile, the rise of virtual reality (VR) technology in recent years has provided researchers with a novel research approach, allowing for a more in-depth exploration of this impact from a new perspective.

1.2. Thesis Objectives

In an open plan office environment, a noise level of a 5 dB reduction does not accurately reflect the actual distress experienced by employees. It merely indicates the intensity of noise [12]. The characteristics of noise, such as tonality, fluctuations, roughness, can have psychological effects on individuals. Without taking into account these characteristics, it impacts play a crucial role in shaping employees' perception and performance.

Quantifying noise levels does not accurately capture the true annoyance experienced by workers in the open space office, as numerical measurements often hold little significance for them who have no knowledge of building acoustics. Instead, a more subjective assessment is necessary to truly understand and evaluate their perception of noise. The objective of this study was to utilize VR technology to assess participants' subjective response to both good signal speech noise and bad signal speech noise experienced in an open space office. Considering that the design of office acoustics can profoundly influence employee health, productivity, and overall well-being, it is crucial to prioritize how speech sources impact office workers' satisfaction.

By integrating traditional VR applications with a high-quality binaural synthesis technique, participants were presented with audiovisual stimuli, engaged in longer duration tasks, and exposed to realistically simulated office noise. Moreover, the laboratory ensured well-controlled acoustic conditions, ensuring consistency among participants and creating a realistic model of the challenging scenarios heard by the participants.

1.3. Study outline

This research paper comprises of five chapters. The first chapter is the introduction of effects of sound masking noise on workers' perception and performance, which is mainly used to introduce the background, purpose and significance of this topic. It emphasizes the importance of studying the field of sound masking system. Chapter Two mainly focuses on the literature review stage. To ensure readers of this paper have a great and clear understanding of the research scope, it reviews the results of previous relevant research and proposes the theoretical framework adopted for the study.

Chapter Three is about acoustic and 3D model modeling stage and experimental measurement testing phase. The model in the unity can ensure that the model can accurately reflect the structure and characteristics of the research object. This stage also explains the design experimental plan, including measurement parameters and experimental conditions. Chapter four organizes and analyzes the data obtained from four questionnaires of experimental measurements in the Concordia University's lab, using visualization tools to display relevant properties and experimental results of acoustic and 3D models. Chapter five is the evaluation and conclusion stage. The author describes the main findings and conclusions of the study, making some valuable suggestions for possible improvements or optimizations in the near future and discussing the limitations of this whole research.

1.4 Definition of terms

For the purpose of ensuring clarity and precision in the discussion of this paper, it is definitely important to give a comprehensive and clear explanation of key terms. The following section nourishes to define and clarify the terms that form the foundational framework for this research.

1. Nature of sound

Sound is the perception experienced by the human ear due to swift variations in air pressure in the natural world [13].

2. sound waves

Sound waves possess various characteristics, including amplitude, frequency, time, velocity, and wavelength. Among these characteristics, wavelength is the most significant feature of a sound wave. The wavelength can be referred to the distance between adjacent crests or identical points within successive cycles of a waveform signal. The reason is that it propagates through space or along a wire [14].

$$\lambda = \frac{c}{f}$$

where

λ = wavelength (m)

c = velocity of wave propagation (m / s)

f = frequency (Hz)

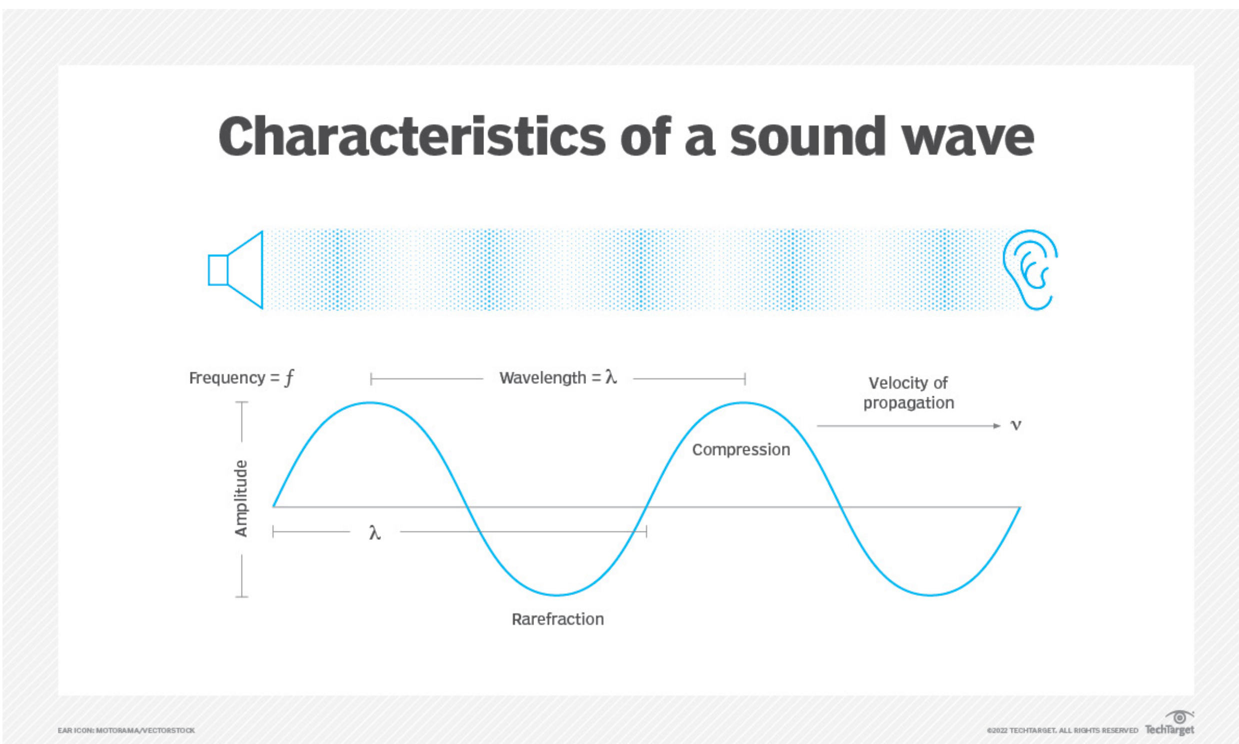


Figure 3. Soundwaves vibrate the air, sending the audio through the outer ear to the eardrum, which vibrates to send the sound information to the brain for processing [14]

3. Pink noise

It is a sound signal with equal energy per octave, meaning that each octave carries the same amount of energy of power. Pink noise is always described as having a hissing or shushing sound and is commonly found in natural systems and phenomena [15].

4. Frequency

The back-and-forth motion of an object produces a continuous sound at regular intervals. The time interval in which this movement occurs repeatedly is called a period. For example, if the human heart beats 72 times per minute, then the period is the total time (which is 60 seconds) divided by the number of beats (72 times), giving a result of 0.83 seconds per beat. The period can be reversed to get the number of complete cycles of motion within a given time interval, which is called frequency [15].

$$f = \frac{1}{T}$$

where

f = frequency (cycles per second or Hz)

T = time period per cycle (s)

Frequency is measured in Hertz (Hz), which stands for cycles per second, named after physicist Heinrich Hertz (1857–1894) [15].

5. Frequency Spectrum

If human beings were to measure the strength of the sound produced by a specific musical note and create a graph showing sound level versus frequency, they would obtain a chart known as a spectrum [15].

6. Equivalent A-weighted sound pressure level (L_{Aeq}):

It is a constant sound pressure level, possessing the same overall sound energy as the actual sound within the designated time period. The result is expressed in dB(A) [16].

7. Binaural Sound

By using a dummy head with a headset and listening to the sound through stereo headphones, many of the three-dimensional spatial properties heard in real life can be reproduced in the recording. This recording technique is called binaural reproduction. When sound is recorded binaurally, events occurring on the sides or back of our heads are clearly localized. Sound sources located in front sound like they originate from the top of our head, overhead, or even behind [15].

8. Auralization

Once the room response has been established for a specific source and receiver position and orientation, the resulting impulse response can be convolved with a dry (anechoic) audio signal. This process, known as auralization, calculating results to simulate the playback of sound within the room [15].

9. How sound is perceived

It is a good question to ask what really happens when sound waves reach the outer ear of human beings? Upon reaching the outer ear, sound waves will go through the following processes: the auricle or pinna collects and channels them through the ear canal, which can amplify the sound. The incoming soundwaves go to an oval-shaped membrane at the end of the ear canal is the so-called eardrum. They can truly cause the eardrum to vibrate once the soundwaves come to the eardrum. The vibrations are transmitted to three small bones known as the incus, malleus, and stapes [14].

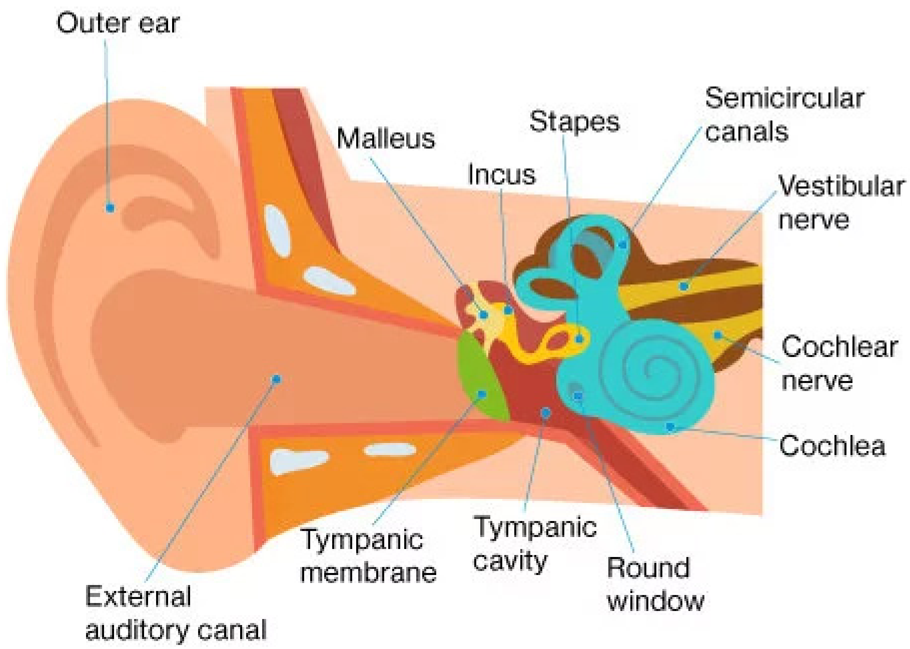


Figure 4 . Internal anatomy of the ear [17]

10. Sound pressure level (SPL):

The sound pressure level is a widely used measure to gauge how strong a sound wave is. It aligns closely with how humans perceive loudness and can be easily measured using affordable instruments [15].

$$SPL = 10.\log_{10}\left(\frac{p^2}{p_0^2}\right)$$

where

SPL (dB) = Sound pressure level in decibel

P (Pa) = Sound pressure in Pascal

P_O = Reference sound pressure level in Pascal

Chapter 2. Literature review

Sound masking systems are the technical methodology designed to reduce the impact of ambient noise by introducing specific sounds to create a more controlled and comfortable work environment for open-plan offices. VR technology by using Oculus Quest 2 and headphone provides a tool to imitate the working environment in a controlled setting, allowing participants to interact with the work environment in a novel way. Combining the two areas definitely gives researchers the great opportunity to dig deeper into how sound masking impacts employee perception and performance in open plan offices.

2.1. VR technology

The Britannica Dictionary explains VR as: "an artificial world of images and sounds created by a computer that is affected by the actions of a person who is experiencing it". The VR technology can be clearly described as a product of computer technology that simulates some specific environment by rendering visuals and audio, allowing people to have an immersive experience [18].

In a real open plan office, conducting these types of studies may be limited by the changing dynamic acoustics. Acoustics is not an integral part of the experimental design. Even if the task itself does not vary, significant differences may occur during experimental testing due to noise from electrical equipment, mechanical equipment, human voices, traffic, or other surrounding environments. For economic and practical reasons, researchers in the university do not want to make any physical modifications to the on-site open plan office. Actually, people simply want to alter the indoor acoustic conditions of the open-plan office, the type, direction, and location of the involved sound sources, and examine the sequence of conditions. Regardless of the research field, controlling external and confounding variables is a crucial aspect to ensure the internal validity of results. However, it becomes particularly challenging during field studies recently [19]. The reason why the VR method has been chosen to use to conduct this sound masking system experiment is because VR technology can control the environmental stimulation experienced by participants. At the same time, maintaining the consistency of the experiments under four different conditions with 20 people participating as much as possible. At the same time, the consistency of the experiments under four different conditions with 20 people participating can be maintained as much as possible. Each virtual reality scene can continuously present the same situation as the actual open plan office scene.

VR technology can present realistic visual environments and simulate real spaces (such as open plan offices) while maintaining a controlled acoustic environment in the laboratory. The highly controlled and immersive environment allows for the precise control of stimuli, researchers can investigate subjective testing and mechanisms in a highly controlled and good immersive setting [20]. Immersion allows participants to feel connected to the real life in a virtual environment. This situation makes it possible to create high-quality virtual spaces with quasi-reality impressions, allowing the study of quite complex behaviors under realistic conditions [21]. Conducting experiments by using VR technology, it can design a test paradigm that can perform perceptual assessment of noise stimuli in open plan offices. It can also make the environment and external noise more realistic and controllable, giving sound masking experiments more situational characteristics [22].

Nowadays, in the common VR applications, in order to achieve a stereoscopic and more natural view, utilizing the human visual system to present a computer-generated representation to each eye. For the purpose of enhancing immersion in virtual scenes in the lab, experimenters need an audio system that performed spatial sound in the VR scene. However, it is certainly not simple for the researchers to add the "convincing" spatial sound to a visual virtual scene. Experimenters must synthesize and reproduce the position, direction, level, and distance of each sound source in the VR scene based on visual stimuli [23].

2.2. Utilization of Virtual Acoustic Environments in the conduct of auditory experiments

For the models in VR, sound is indispensable. Auralization is a process of imitating and generating sounds through artificial technical means [24] [25]. Auralization is a technical term introduced by Kleiner et al. (1993), which means the propagation of sound presented in a modeling space for the purpose of simulating acoustics [18]. This section provides an in-depth exploration of the application of acoustic virtual reality (AVR) in creating architectural acoustic simulation experiences from a technical perspective.

At Concordia University's lab, researchers focus on conducting auditory experiments in VR. Researchers conduct the experiments in the lab by using Unity software (cited from Unity Technologies) [25] and a framework developed by Virtual Acoustic (cited from the Institute of Hearing Technology and Acoustics at RWTH Aachen, Germany) [26]. This concept means integrating an acoustics simulation framework into virtual reality [27]. The Virtual Acoustics (VA) mentioned above is a real-time sound simulation framework for scientific purposes. It not only provides modules and interfaces for auditory experiments, but also has audio functions for audio-visual demonstrations or multi-modal experiments. It is an open source and fully controllable system, and it meet the principles of reproducible research. Researchers can download libraries, research applications and documentation from virtualacoustics.org [28]. By applying physics-based source emission and sound propagation models, VA enables realistic rendering of virtual scenes from purely synthetic data. VA's modular design gives a variety of rendering modules through using different sound propagation assumptions. In this case, this can allow a variety of complex indoor and outdoor scenes to be rendered with adjustable complexity. Constructed on a similar modular concept, VA can flexibly reproduce sound, whether through headphones or speaker arrays. To achieve this goal, the signal is spatially localized by using binaural synthesis, high-order surround or VBAP [29]. For the best performance in the frame, VA is implemented in C++ and features a communication API over the network. It interfaces with several programming languages, such as C#, Matlab, Python, and C++, as well as plugins for Unity software, known as VAUnity. The VAUnity plugin can be used in conjunction with GameObjects in Unity software and communicates with VA software. The real-time sound simulation framework is built on VAUnity, showing in Figure 5. As shown above, it rules virtual sound sources and monitors in the scene. It includes different extensions and plug-ins for answering multiple-choice questions, events in a soundscape, and events in a virtual environment. The listening experiment is organized as a queue that encompasses various elements of the experiment. Through this approach, it is possible to halt and initiate source playback at a specific point in the questionnaire survey [27]. Thanks to the modular implementation concept, arbitrary renderer and playback instances can be combined and executed concurrently. The available processing power of the host computer running the VA application is the only limitation. This framework provides options for many uses when designing and performing subjective auditory experiments [28].

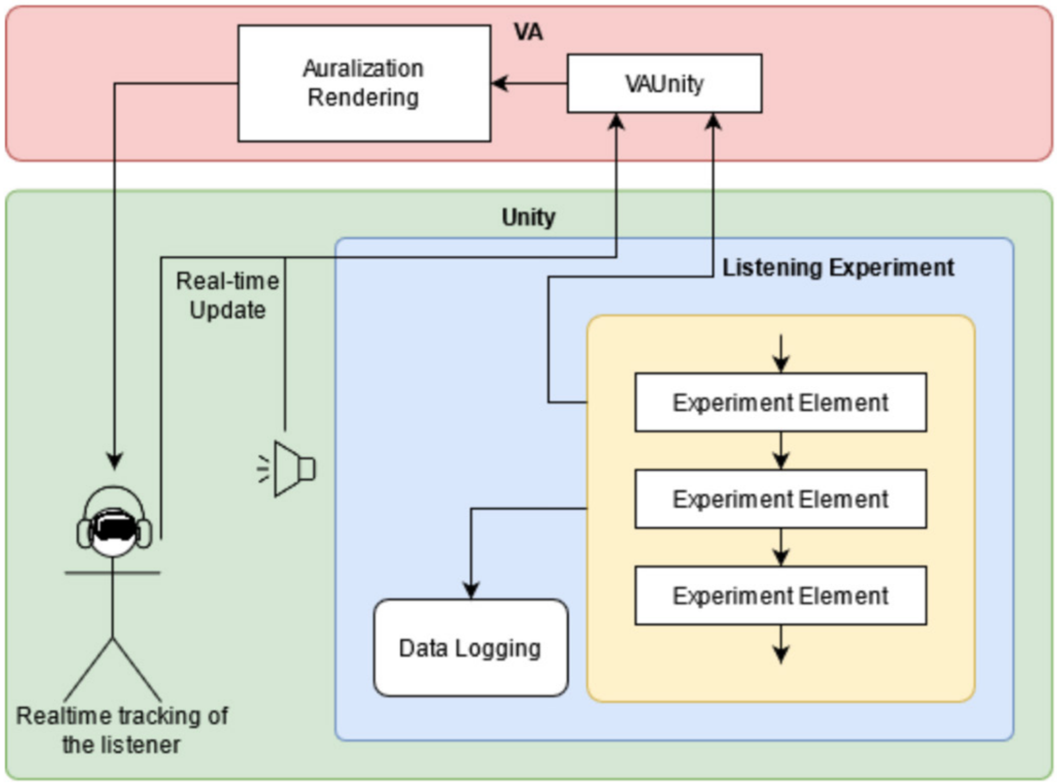


Figure 5. integrating a framework into a VR project [27]

In order to create the virtual scenes for auditory testing in VR and generate more workable subjective testing for sound masking systems in the real-time environments, professional gaming and virtual reality engine software Unity software is serviced by the researchers. Unity, is a versatile game engine supporting both 2D and 3D game engine, developed by Unity Technologies [25]. Unity is one of the greatest game engines and visual rendering software, and it is trouble-free to use compare with other available game engines [22]. Moreover, it contains all the necessary tools that researchers need [28]. The import function of architecture and structure directly imported from third-party commercial software (such as SketchUp [30], AutoCAD [31], etc.) is also supported by it.

When creating a virtual architectural scene, choosing a suitable 3D architectural modeling software is an indispensable step. Revit-2021 works for designing the architectural model of an open plan office. Researchers import the model created in Revit into Unity, which combines the remaining modeling features of the scene, such as audio sources (i.e. noise sources), listeners (i.e. receivers), camera views (i.e. visualizing the scene) and interactive scenes (i.e. for listening tests and psychoacoustics assessment scenario) [22]. The GameObjects which mentioned above applied in the unity have different properties and extensions, such as audio sources, listeners and camera views. The properties and extensions are coded through using the C# programming language [27]. To create an audiovisual experience, in addition to audio reproduction, researchers must provide experimental participants with high-quality visual like the real-world situation. By integrating VA into an extended Unity-based environment, visual feedback can be easily rendered for head-mounted displays such as the Oculus Quest 2 [28].

The generation of an acoustic scene has been shown below. Also, how the test subject will be perceived during the experiment has been proposed.

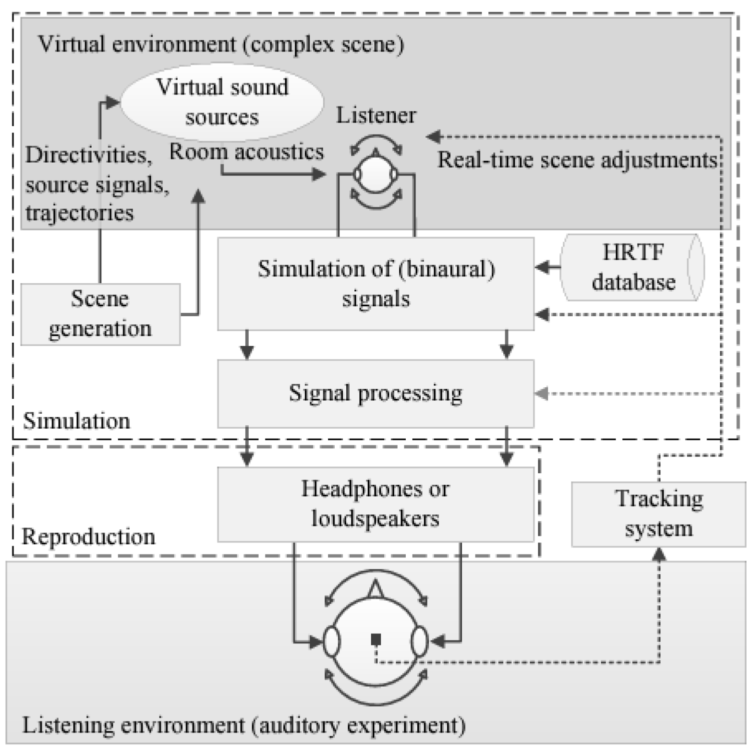


Figure 6. a conceptual overview of the illustration how to create and reproduce in a scene [28]

Usually, virtual scenes are represented by sound source definitions and room acoustic parameters. The output signal is simulated in real time and reproduced via headphones or a speaker-based reproduction system. The output signal is simulated in real time and reproduced through either headphones or speaker-based reproduction systems. When utilizing binaural headphones or loudspeaker reproduction, the tracking system captures the user's movements, thereby affecting the analog output signal. Depending on the nature of the experiment, the participants are required to speak out their perceptions, such as responding to questionnaires, or undertaking designated tasks to convey their perceptions. This kind of acoustic scenario should involve at least one sound source [28].

2. 3 Sound masking system

Human auditory perception is a phenomenon involving complex physiological and psychological processes. When virtual walking through a building complex created in Unity, auditory information can significantly complement the visual information and overall impression. In turn, this imbues the entire research question with deeper significance [21].

In an immersive experience, auditory perception is quite important to users, as it serves as a vital supplementary source of information. Actually, this circumstance not only enhances the realism and believability of the virtual environment, but also improved users' sense of direction within it [22] [32]. Besides, it has been demonstrated that unattended background speech can affect several cognitive tasks, short-term memory [33], mental arithmetic [34], reading comprehension [35], and proofreading [36].

2.3.1 Sound source level for sound masking system

Speech intelligibility can be defined as the clarity with which a person speaks, ensuring that listeners can understand the content of their speech [37]. Speech intelligibility specifically refers to the clarity and understandability of spoken language to the listener. Especially, it measures how easily and accurately a person can understand words and information conveyed through speech [38]. To ensure that a normal-hearing listener can fully understand a sentence, the speech signal-to-noise ratio (the difference between the speech level and the ambient background noise level) should be at least 15 dB(A) [39]. The same theory is also supported by the author Peng Jianxin, that is, under the same reverberation time conditions, there is no obvious difference when the Mandarin speech intelligibility score and the signal-to-noise ratio are not less than 15 dBA [40].

2.3.2 Indirect Sound Masking Technology in open-plan offices

Indirect Sound Masking Technology uses the technology that speakers radiate sound directly downward into the open plan office rather than into the ceiling cavity above.

The non-uniformity caused by openings in the ceiling for HVAC or lighting fixtures, ventilation ducts in building structural elements, fireproof treatments, large ductwork, or other mechanical components in cavities, The main advantage of Indirect Sound Masking Technology is that it no longer has any significant impact on the spatial distribution of the masked sound. System designers and sound designers only need to provide a well-defined and simple layout of masked loudspeakers without precise knowledge or consideration of the architectural elements above the ceiling. They can ensure a very uniform coverage of the area, which saves time and money in the design process. This leads to the conclusion that indirect Sound Masking Technology's masking sounds and ambient music have great spatial uniformity. Basically, there are virtually no dead spots throughout the entire space. Even if the ventilation space is blocked in the building structure, the spatial uniformity is also significantly superior to ceiling-mounted or drywall-mounted direct-field, downward-emitting speakers. These systems ensure optimal distribution of sound frequencies, allowing the system to provide effective masking for personnel in open plan offices at lower volumes. This reduces potential disturbances and maintains acoustic effectiveness throughout the building. In terms of sound masking performance, coverage uniformity, electrical safety and visual aesthetics, this system is perfectly suited for exposed ceiling designs and suspended ceiling systems. They allow for a more flexible, cleaner, faster and more economical installation compared to sound masking in ceiling as they eliminate the need to drill holes in the ceiling and acoustic tiles [41] [42].

Chapter 3. Methodology

In the following chapters, researcher will delve into how the combination of sound masking technology and VR technology can provide human beings with deeper insights and discuss the research methods and key findings. The outcomes of this study will provide organizations with significant insights on how to enhance employee perception and performance in the open plan offices, thereby driving further innovation and improvement in the workplace.

3.1. Experimental Environment

The experiment took place in the acoustic lab of EV Building at Concordia University in Canada. Participants were seated in a booth within the acoustic lab (EV Building, S3.412). The measurement of booth is 2997mm (L) x 2718mm (W) x 2235mm (H), manufactured by ECKEL Noise Control Technology [43]. The 25mm pass-through space of booth provides a tiny but enough area for routing the necessary lines connecting the computer with VR device and headphones. The high-standard booth generally provides privacy and minimized external distractions for doing the experiment. The booth's temperature and relative humidity were monitored using a Govee Thermo-Hygrometer. The temperature within the booth in the acoustic lab is maintained at 21.3 degrees Celsius, with an accuracy of ± 0.4 degrees Celsius. Additionally, the humidity level within the booth is maintained at 40%, with a precision of ± 2%.

In this study, Unity has been chosen as the 3D modeling engine, and Virtual Acoustic is utilized as the auditory simulation plugin. The acoustic properties of objects are provided by Virtual Acoustic. The headphones provided for the experience are the big-league SENNHEISER model HD 650, ensuring outstanding audio quality. The VR device utilized is the Oculus Quest 2, enhancing the stable and immersive nature of the virtual reality environment. The experiment was conducted on an LG Intel computer running Unity game project, allowing for efficient and smooth execution of the VR math game. The researcher was able to observe and monitor all the activities and interactions of the participants during their immersion from interface of unity and window's transparent glass of the booth, which means the researcher was aware of the real-time progress of the experiment and she can accordingly prepare the next task in advance. Furthermore, if anything happened during the experiment, the researcher had the ability to stop the game. The experiment's environment is a 3D virtual environment designed by Unity to have a similar open plan office setting. The L-shaped open-plan office space spans approximately 68.5 square meters in floor area and stands at a height of 2.7 meters. Like Figure 7, the virtual reality environment has been programmed to include familiar office elements like a computer screen, furniture includes 5 tables, 21 chairs, 4 windows, and 3 diffusers, as well as 3 doors. In the room, there are no visible measurement devices or other interferences.

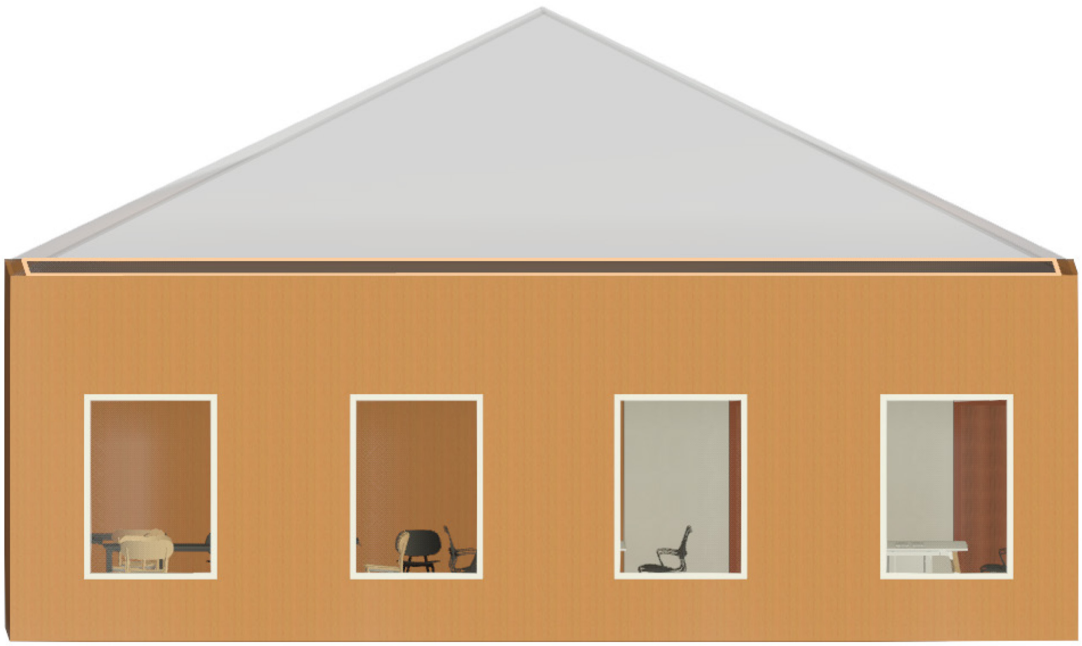


Figure 7. The exterior appearance of an open-plan office

Figure 8. Open Plan Office Layout Diagram

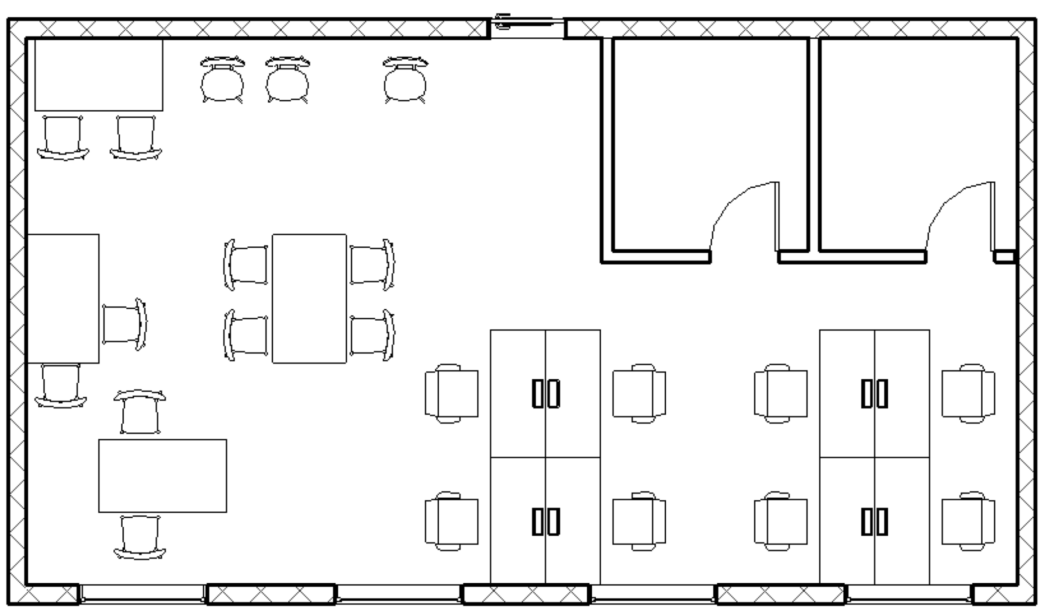


Figure 9. Floor plan of Open Plan Office

The model and the arrangement of four source positions and one receiver position are shown in figure10.

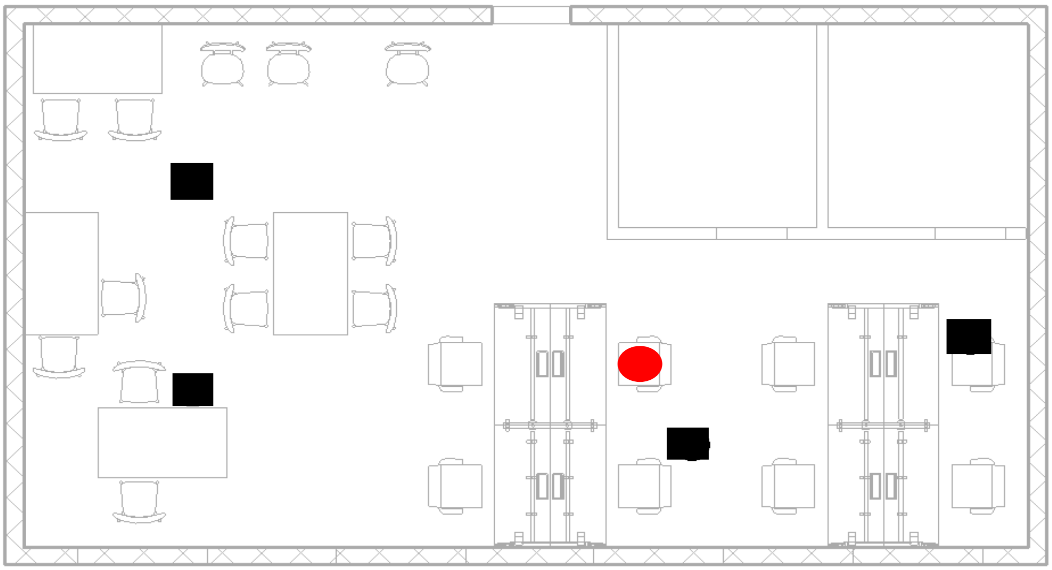


Figure 10. Planar diagram of four source positions and one receiver location

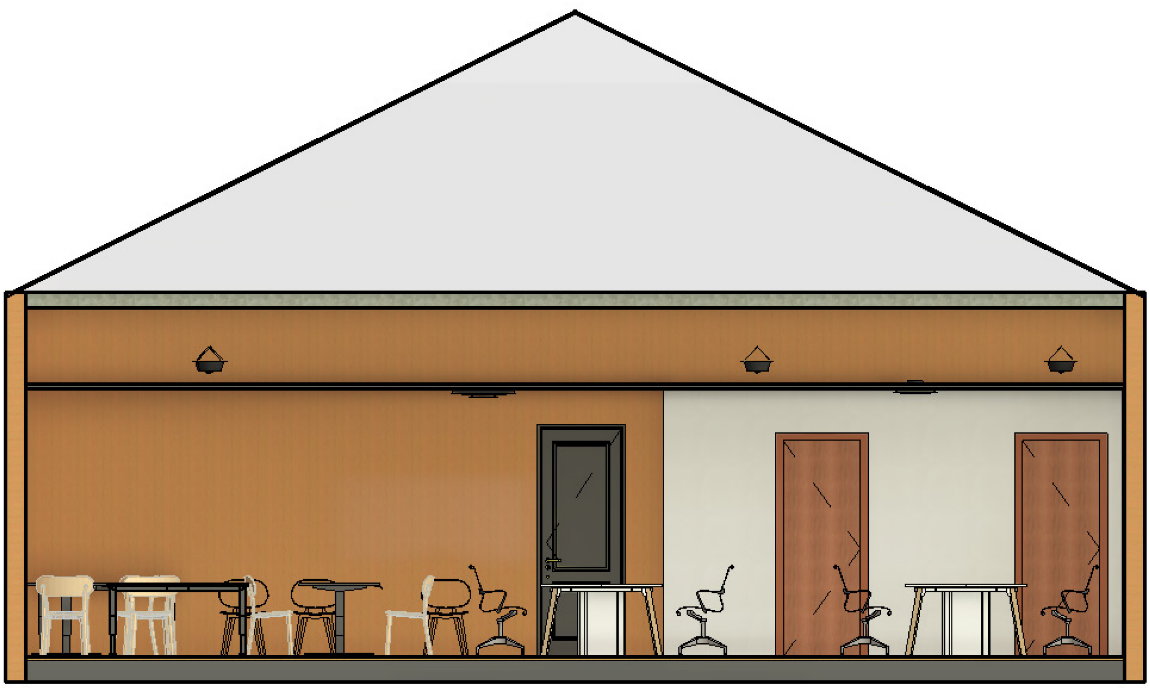


Figure 11. Side view diagram

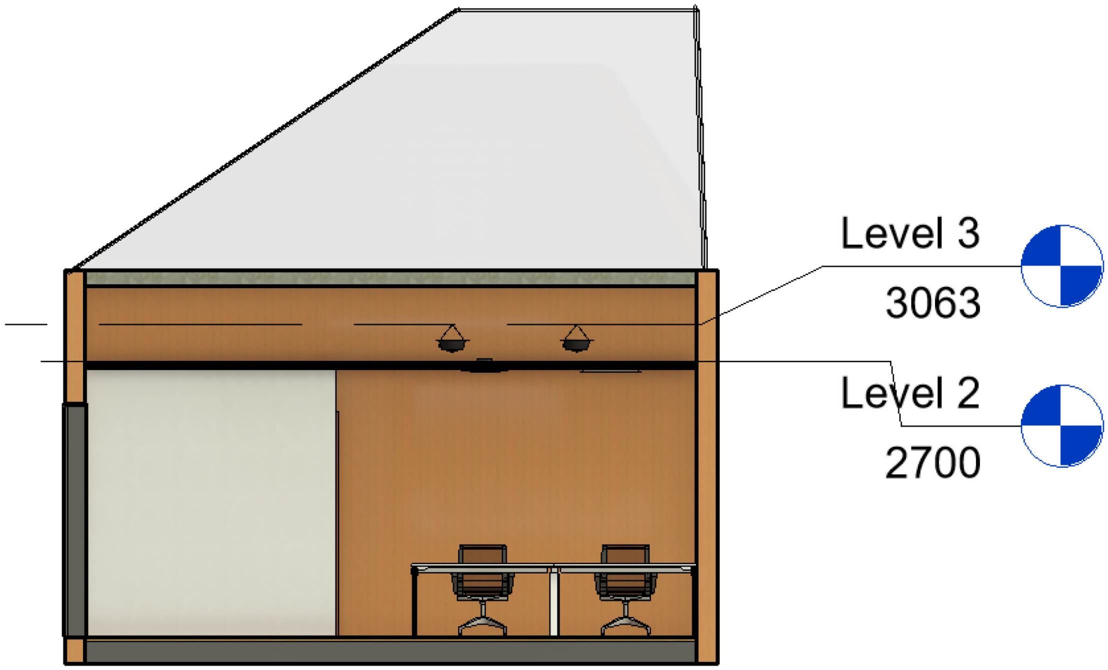


Figure 12. Side view diagram 2

3.2. Sound materials

During the VR experience, all the participants were exposed to four different noise conditions. Wearing the VR device exposes participants to background noise levels of 38 dBA and 50 dBA, with a speech signal at 53 dBA. The Signal-to-Noise Ratio (SNR) is 15 for the 38 dBA background noise and 3 for the 50 dBA background noise. For the speech content, the UW/NU Corpus, a collaboration between the University of Washington and Northwestern University, comprises recordings and textgrids featuring 20 speakers (10 from Northern Cities and 10 from the Pacific Northwest) reading 180 Harvard IEEE sentences [44]. All the sentence texts involved in the speech are gotten from the IEEE “Harvard” set [45]. The corpus contains WAV format audio files sampled at 44.1 kHz with 16-bit depth. These files consist of readings of 180 sentences by 20 distinct speakers, comprising 5 males and 5 females from each of two American English dialect regions: the Pacific Northwest and the Northern Cities. All audio files have been RMS-normalized to ensure intensity across the corpus recordings [33]. The sound levels of all the sentences were modified to the same A-weighted level, correcting for variations in speech effort by using the software BK connect [46]. Furthermore, the spectrum of each speaker was modified so that the octave band levels were deviating from the speech spectrum shape of the data detected on-site by no more than 2dB. Each speech segment lasts between 3 to 5 seconds, with 3 to 5 seconds of silence between each segment. The consecutive segments separated by silence are not taken from the same chapter, so there's no continuous plot. Therefore, a speaker will not be in an active state consecutively twice. Besides, all the speeches are disjointed. The sample resembles a typical office environment where speech and silence alternate arbitrarily. The final playback recording length is 40 minutes for each one.

Table 1 Description of the actual sound recording used in the experiment.

	Sound types	L_{Aeq}
Control group	Ambient sound (control)	
Background music	Pink noise 1	38dBA
	Pink noise 2	50dBA
Background noise	Speech signal	53dBA

Virtual acoustics generated and played four noise conditions during the experiment. The study utilized four different noise conditions within the non-harmful range. These noise conditions were played once the game started. The selection of 38 dBA aimed to simulate the background noise for a typically quiet office environment, while 50 dBA aimed to simulate the sound of air conditioners commonly heard in office spaces [47]. Using pink noise as a background noise is advantageous because it closely similar to HVAC noise. People are likely accustomed to the background hum of HVAC systems, which making pink noise less noticeable and easier to get used to. The order of playing four noise conditions for all the participants was randomized to reduce any potential order effects from other three noise conditions. The detailed explanation of the order for preforming the experiment can be found in Appendix A. The acoustic conditions in the laboratory performed in the acoustic lab are well-controlled, and consistency is maintained among participants.

Table 2. Speech spectrum for all the conditions

Frequency (Hz)	50 (dBA)	38 (dBA)	Speech (dBA)	50 (dBA) with Speech	38 (dBA) with Speech
20	51	50	40	51	50
25	50	49	45	50	49
31.5	49	48	42	48	47
40	50	50	35	50	49
50	50	49	34	50	49
63	44	44	32	44	44
80	42	45	28	42	44
100	45	44	22	45	44
125	45	44	23	45	44
160	43	38	24	43	38
200	46	36	35	46	38
250	42	32	28	42	34
315	42	30	27	42	32
400	40	28	38	42	38
500	37	22	36	40	36
630	37	22	33	39	33
800	33	18	27	34	28
1000	35	20	34	38	34
1250	37	23	38	41	39
1600	40	25	37	43	37
2000	39	25	38	43	38
2500	38	27	36	41	36
3150	39	28	38	42	38
4000	41	29	32	42	34

5000	40	27	42	44	43
6300	35	24	33	36	33
8000	31	22	18	31	24
10000	26	18	8	26	18
12500	14	9	8	17	12
16000	9	6	6	13	7
20000	7	6	6	7	6

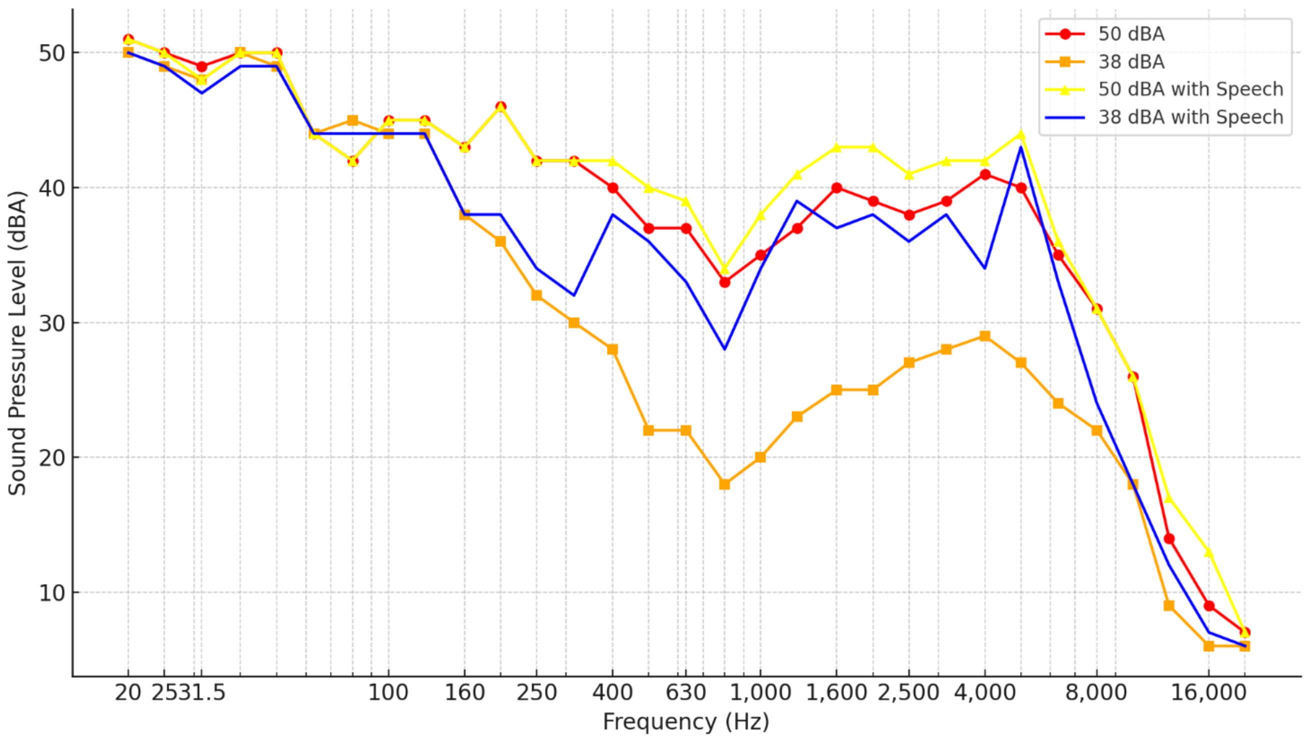


Figure 13. Line chart for four conditions.

3.3. Experimental design and procedure

The study recruited participants from Concordia University. Before being a part of the experiment, all potential participants confirmed they have normal hearing and vision status. In order to ensure the impartiality and reliability of experimental data, researchers require subjects to maintain adequate sleep and a healthy diet before participating in the experiment. This is to mitigate the influence of emotional fluctuations on experimental results. Furthermore, for the purpose of preventing them from having a practice effect, the participants in the experiment had never participated in a similar experiment before. At the end, none of the participants in the experiment had experienced major mood swings recently. A special criterion was set for individuals between the ages of 25 and 45, which means participants with a history of hearing impairments or vision problems were excluded. There were 10 participants involved in the game, and they were compensated for their participation in a two-hour VR experience with a $30 Amazon gift card.

Participants scheduled their research survey appointments by using Calendly, an online scheduling tool. Data collection occurred between 9 a.m. and 5 p.m. in winter, and the deliberate timeframe is chosen to provide participants with the regular office conditions. They come to the lab four different times on different days for the minimal impaction. Each participant completed the experiment individually under the supervision of the researcher. Before starting the experiment, by demonstrating the slides, the researcher gave them a comprehensive description of the steps involved. Participants were required to read and sign the Information and Consent Form, as well as the Protocol Form, indicating their understanding and consent to taking part in the experiment. Prior to the trial, there were two parts to the questionnaire. As shown in Table 2, before conducting the experiment, participants must fill out two sections of the information survey. Completing the basic demographic forms is the first step. The second part is to fill in the Weinstein Noise Sensitivity Scale. This circumstance makes it possible to investigate the impact of different personal characteristics on visual cognitive tasks under different acoustic environments in more detail.

Table 3.comparisons of measured and preset values

The questionnaire	**Questions**	**Description**
Personal information	Name, Gender, Age	

Weinstein Noise Sensitivity Scale	21 questions	A psychometric instrument designed to measure an individual's sensitivity to noise. On a 6-point Likert scale, 1 indicates complete agreement, while 6 indicates complete disagreement [48].

Due to the novelty, participants may pay more attention to the images of the virtual environment rather than the specific tasks. This situation may cause their attention to be at something else, thus affecting their feeling and perception during the experiment. That is the reason that it needs to take some time for participants to get used to the feeling of wearing the device. Researchers provide sufficient time for participants to adjust to the device to mitigate the potential impact of novelty and be familiar with the surroundings, ensuring that their experience is more consistent with the goals of the experiment. Users also need to adjust the Oculus Quest 2 to ensure dual-eye focus for obtaining clear images in virtual reality world. Once the participants started playing the VR game, they would find themselves seated at a designated chair, facing a computer screen which requires them to perform the math calculations, and enjoying a fully immersive 360-degree view of the open space office environment.

Besides, participants started the practice trials in silence, allowing them to familiarize themselves with the math task, particularly for the second task. Before starting the tasks, participants engaged in practice trials for approximately 3 minutes in silence, which allowed them to familiarize themselves with the VR environment and Oculus Quest 2 touch, as well as the game mechanics.

There are two game tasks for experiments. The reason for choosing math calculations for the experiment is that they closely resemble the tasks performed in an open-plan office. For the first phase of the experiment, it is being set as same procedure in the article [49]. By using this method, the 24 calculation questions included first 4 addition problems, then 10 1Digit × 1Digit multiplication problems, and following 10 1 Digit × 2 Digits multiplication problems. All the participants did the math question in different order. The average time for finishing the first task is about 3 minutes, assuring 7.5 seconds for each question.

For the second phase, participants were presented with 108 math questions. Their task was to determine if a reference number displayed on the screen was larger or smaller than the correct answer for the calculation. The 108 calculation questions included first 36 2Digits × 1 Digit multiplication problems (there are 10 questions from the first task), and then 36 2 Digits × 2 Digits multiplication problems, then following 3 Digits × 2 Digits multiplication problems.

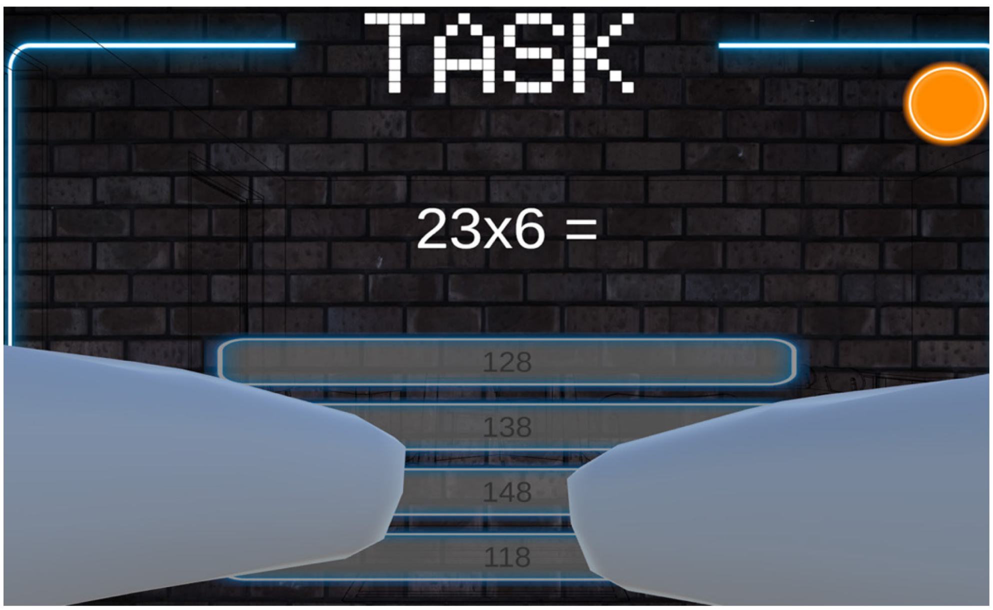


Figure 14. Task 1 (part two)

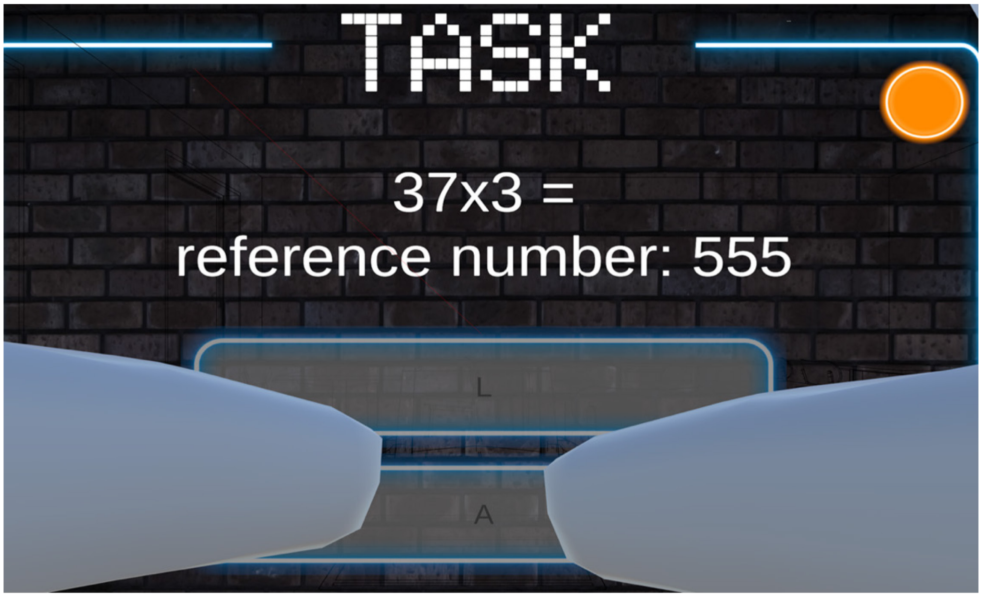


Figure 15. Task 2

All the calculations had four reference numbers: one that was approximately one fifth of the exact answer, two that were approximately five times the precise answer, three that were approximately one half of the exact answer, and four that were approximately twice the exact answer. The four reference numbers are categorized into four lists. The reference numbers were categorized into four lists, each with four reference numbers. The exact answers for the math questions ranged from 9 to 40820. Participants evenly distributed among the questions and lists. The maximum time allocated for completing both tasks was approximately 17 minutes, allowing an average of 9.5 seconds per question. Periodically, the researcher looked through the chamber glass to make sure the individual was safe. In addition, the researcher kept an eye on the computer to see how the task was coming along.

The authors, Kozulin, Ames, and McBrien, suggest that following a 30-min HMD viewing session, there is a reduction in near-field visual acuity immediately [50]. Therefore, the two tasks were designed in approximately 20 minutes, with a 30-second break between the first task and the second task. After completing each section (two tasks), participants were asked to take a paper survey regarding their perceptions of the noise they experienced during the study. The questionnaire surveys were used as the primary research method in this investigation. This survey used the NASA Task Load Index (NASA-TLX) (see Appendix C for the NASA TLX) [51]. The

NASA-TLX questionnaire is typically used to evaluate the mental, physical, and temporal demands of a task, as well as the perceived effort, frustration, and performance level. Twenty-step bipolar scales ranging from 0 (very low) to 20 (very high) are utilized to gather ratings on these dimensions and the instrument assumes that the combination of these six dimensions effectively represents the "workload" experienced by participants [52].It is primarily used to assess the subjective workload of task performers during task execution, aiming to quantify the level of task load. Every survey was estimated to take approximately 1 minute to complete. To complete this study, they were required to visit the lab four times. The study comprised a total of four sections, with each section having a 7-hour break. Overall, the study's participation required a total of 2 hours. The researcher was present throughout all the test sessions for 10 participants.

3.4. Ethical Considerations

This study obtained ethical approval from the College of Ethics Reviewers (CER) ethics committee. Participants signed information and consent form before participating in the research, as well as the Protocol Form. Besides, their confidentiality and anonymity were ensured throughout the research process. Any personal information collected was stored securely in the acoustic lab of Concordia University and used solely for research purposes. Only researchers work in the acoustic lab have access to all the information related to the participants. Additionally, participants had the right to withdraw from the study at any time before the deadline without any consequences. The potential risks associated with participation were minimal, as the noise levels played during the experiment were within the non-harmful range. Before they attended the study, they were told if they experienced discomfort or dizziness were given the option to terminate their participation immediately. If they felt unwell in any way, the research would send them straight to the clinic at Concordia University, which is just a 5-minute walk from the acoustic lab.

4. Chapter four. Results and discussion

4.1. Measurement Results

The 10 participants are aged between 25 and 39. Exclude one data point as it could potentially skew the results due to the participant's inability to complete the minimum task requirement, which may be considered an outlier. Another two subjects' data also have been excluded from the dataset due to their responses appearing abnormal compared to the rest (outliers). Overall, seven data points were collected. Table 4 shows the traits of the respondents. A mean score of 3 among all the subjects was considered as the standard; scores above 3 indicated the high sensitivity, while scores below 3 were treated as low sensitivity.

Table 4. Demographic information of participants

Characteristics of participants		
Characteristics	**Group**	**Number**
Gender	Male	4
	Female	3
Noise sensitivity	High sensitivity	4
	Low sensitivity	3

Table 5 presents the results of the survey, showcasing the various metrics and data collected from the participants in the acoustic survey. Employing various statistical methods and graphical representations to elucidate the findings is quite important.

Table 5.Presentation of the results of the acoustic survey

Participant	**Speech Presence**	**Background Noise**	**Noise Sensitivity**	**Amount of task completed (out of 3)**	**Accuracy of the task (%)**	**NASA Task Load Index (out of 21)**
1	No	38	3.8	1.00	98.86	9.50

2	No	38	2.4	1.47	100.00	6.00
3	No	38	3.2	0.98	100.00	3.75
4	No	38	2.8	2.38	100.00	5.25
5	No	38	2.4	1.70	100.00	3.50
6	No	38	3.4	1.70	100.00	11.50
7	No	38	3.3	1.00	92.00	14.50
1	Yes	38	3.8	0.70	93.00	15.00
2	Yes	38	2.4	2.53	97.00	8.50
3	Yes	38	3.2	1.34	100.00	4.00
4	Yes	38	2.8	2.31	100.00	6.38
5	Yes	38	2.4	1.80	100.00	6.00
6	Yes	38	3.4	1.38	100.00	13.00
7	Yes	38	3.3	1.00	98.43	14.00
1	No	50	3.8	1.15	82.00	14.00
2	No	50	2.4	2.33	96.00	8.75
3	No	50	3.2	1.25	100.00	6.25
4	No	50	2.8	2.15	99.00	8.88
5	No	50	2.4	1.83	100.00	6.75
6	No	50	3.4	0.98	90.00	14.00
7	No	50	3.3	1.00	75.00	15.50
1	Yes	50	3.8	0.90	98.86	17.75
2	Yes	50	2.4	2.62	100.00	10.00
3	Yes	50	3.2	1.00	100.00	7.75
4	Yes	50	2.8	1.70	98.00	10.50
5	Yes	50	2.4	1.73	100.00	10.00
6	Yes	50	3.4	1.30	100.00	16.25
7	Yes	50	3.3	1.00	100.00	17.00

4.1.1 Impact of Noise Types on Task Performance

The dataset presents the performance of tasks under different acoustic conditions, specifically at noise levels of 38 dBA and 50 dBA, both with and without speech. At 38 dBA, participants completed an average of 1.46 tasks out of 3, with a standard deviation of 0.52. With speech at the same noise level, the average increased slightly to 1.58 tasks, but the standard deviation was higher at 0.67. At 50 dBA, the average task completion was 1.53, with a standard deviation of 0.57. When speech was added at 50 dBA, the average dropped to 1.46 tasks, with a standard deviation of 0.61.

At 38 dBA, the average accuracy was 98.69% with a standard deviation of 2.98. When speech was added, the average accuracy slightly decreased to 98.35%, and the standard deviation decreased to 2.62. At 50 dBA, the average accuracy significantly dropped to 91.71%, with a high standard deviation of 9.88, indicating varied performance among participants. When speech was added at 50 dBA, the average accuracy greatly increased to 99.55%, and the standard deviation decreased to 0.81.This result suggests that the presence of speech, especially at higher noise levels, might have a differential impact on task completion and accuracy rates.

Speech and background noise undoubtedly have an impact on how many and how accurately people do activities, but the specific degree of impact needs to be determined through analysis. There were no significant differences in the number of tasks completed across conditions. This suggests that the presence of speech or the level of background noise (38 dBA vs. 50 dBA) did not have a significant impact on the amount of work completed by participants. Stability of task completion across conditions: With averages ranging from 1.46 to 1.58, the data revealed a generally steady pattern of task completion across conditions. This consistency suggests that neither the presence of speech nor the intensity of background noise (38 dBA vs. 50 dBA) significantly changed the amount of work participants were able to accomplish. This data may suggest that, despite varying levels of auditory interference, each participant maintained nearly consistent levels of work output.

However, the accuracy of the task showed large differences. Specifically, the fluctuation in accuracy highlights the sensitivity to the level of noise. The tiny difference in accuracy between the 38 dBA conditions (with and without speech) suggests that adding speech has a negligible impact on performance at lower noise levels. This could indicate a threshold effect, where the impact of auditory elements on task performance becomes significant only beyond a certain level of noise intensity. The accuracy of the task performed at 50 dBA and no speech was significantly lower (91.71%) compared to the other conditions. This situation means that higher levels of background noise can have a negative impact on task performance. The standard deviation indicates that under the condition of no speech at 50 dBA, the variability of accuracy is the highest. This circumstance suggests that participants' responses varied the most under this condition, which may indicate differences in their sensitivity to higher levels of background noise. This variability may reflect different individual thresholds for noise interference. Interestingly, when the experimenters added speech to 50 dBA background noise, accuracy improved significantly, reaching the highest value of all conditions (99.55%). This may imply that speech in high background noise conditions may have a focusing effect or provide a cognitive support to enhance task accuracy. Additionally, in the absence of speech, performance degradation at higher noise levels highlights the potentially damaging impact of environmental noise on task accuracy. In contrast, introducing sound masking and high-intensity noise can help alleviate this influence. It also appears to enhance human attention or cognitive engagement, leading to greater accuracy on the job.

Means for task completion and accuracy were similar under 38 dBA conditions (with speech and without speech). It is easy to conclude that whether speech is present or not, the impact on task performance is tiny. Under conditions of 38 dBA, the presence of speech slightly increases the number of tasks completed but slightly decreases accuracy. Compared to the condition without speech, the task completion rate is slightly higher with speech (38 dBA). This circumstance suggests that low levels of speech background noise may slightly improve productivity, or at least not significantly impede it. Transitioning from a quiet environment (38 dBA) to a louder environment without speech (50 dBA) slightly increased participants' ability to complete the task. However, this transition clearly impairs the accuracy of task execution. This observation emphasizes that despite a slight increase in the number of tasks, the higher level of noise may adversely affect the thoroughness of task execution.

Task performance accuracy showed greater variability, particularly in the absence of speech at higher noise levels. This difference highlights the different ways in which participating individuals respond to environmental noise, with some responding more disruptively than others.

The type of noise and speech significantly affect task performance, especially for accuracy. While the task completion rate remains relatively stable under all the various conditions, the accuracy fluctuates significantly with the level and type of noise. This analysis suggests that moderate background noise, especially with speech, may not impede task performance and may even slightly improve task performance. However, the absence of higher-level background noise in the absence of speech may adversely affect task accuracy. Understanding these noise factors and their impact on performance helps designers make interventions or strategies to improve overall work performance. In the present circumstances, it can minimize differences among participants to the greatest extent.

4.1.2 Influence of Noise Types on Cognitive Perception.

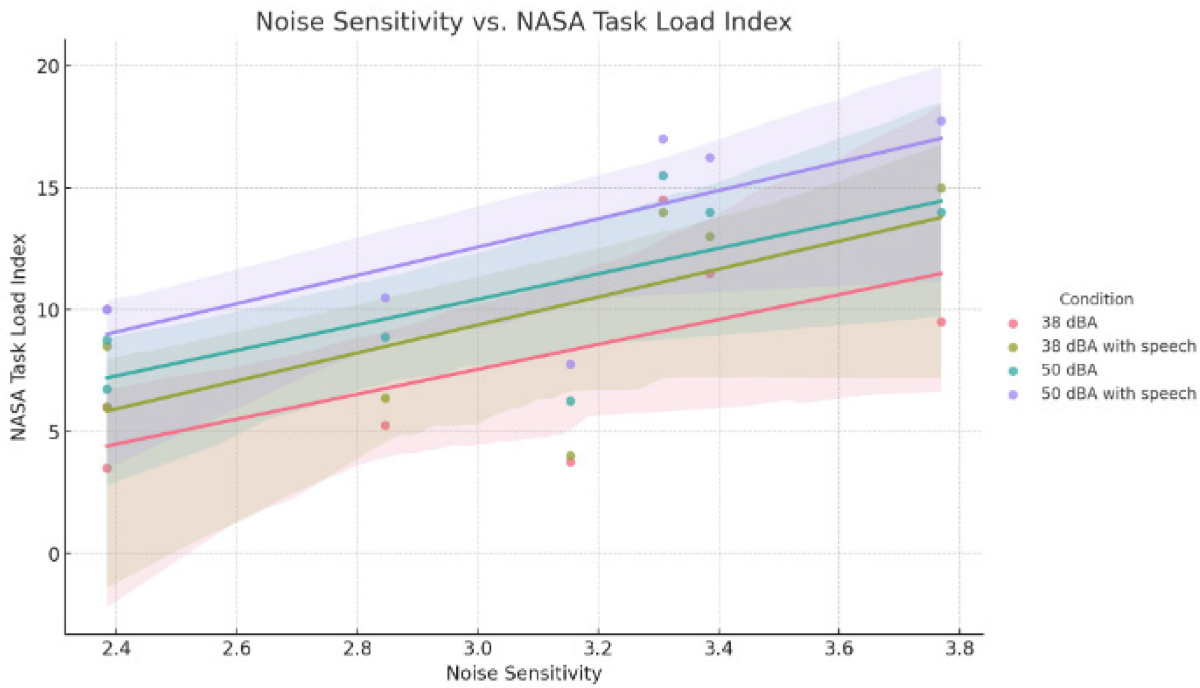
For 38 dBA (quiet condition), the cognitive load is lowest among all conditions, with an average Task Load Index score of 7.71 and standard deviation of 4.20. Introducing speech at 38 dBA slightly increases the average cognitive load to 9.55 with a standard deviation of 4.40, indicating that speech, even at low background noise levels, can raise cognitive demands. At a higher noise level of 50 dBA without speech, the average cognitive load was 10.59, and the standard deviation was 3.81. The highest cognitive load is observed in the 50 dBA with speech condition, with an average score of 12.75 with a standard deviation of 4.09. This condition combines higher noise levels with speech, showcasing the most significant impact on cognitive workload.

The calculated average scores reveal a clear gradient of cognitive load under different noise conditions. Starting from 7.71 (38 dBA) under the quietest condition, to 12.75 (50 dBA with speech) under the loudest and most complex condition, this progression indicates a significant increase in NASA task load index. The results indicate that this trend is consistent regardless of the presence or absence of speech, highlighting that increasing environmental noise is associated with negative impacts on cognitive perception and task performance. All the increasing numbers indicate that speech, possibly due to its rich information nature, may require additional cognitive resources for processing or ignoring, thereby exacerbating the impact of noise on human cognitive performance. This situation may be due to the distracting nature of speech. Even if it is not directly related to the task at hand, it may require extra attention to ignore or deal with. There are differences in sensitivities or coping mechanisms among participants. Besides, the relatively high standard deviations across all conditions also highlight the wide individual differences in NASA task load index across different noise conditions. This kind of difference may be attributable to individual differences in noise sensitivity, task engagement, or other personal factors. This variability may stem from personal characteristics, ability to focus, or even task familiarity, which suggests that people's cognitive responses to environmental and task factors are unique.

4.1.3 Noise Sensitivity and Task Load Relationship

The lines in each graph represent the linear regression fit, indicating the trend between noise sensitivity and task load (measured by NASA-TLX) under each noise condition. The dots represent individual measurements of noise sensitivity and the corresponding NASA-TLX scores under these four noise conditions.

Table 6. The following linear regression graphs depict the relationship between noise sensitivity and the NASA Task Load Index (NASA-TLX) for the four conditions.



The dispersion of data points highlights the individual differences in how noise sensitivity impacts the perceived task load.

Some participants report higher NASA-TLX scores even with lower noise sensitivity, suggesting that other factors may also influence this relationship. In all conditions, the slope for 50 dBA with speech is the highest, indicating that higher noise levels and speech have a significant impact on individuals with high noise sensitivity.

4.2 Correlation Analysis of Noise Sensitivity on Perceived Workload and Task Performance Across Different Acoustic Conditions

Here are the correlation results showing how noise sensitivity relates to the NASA Task Load Index, the amount of task completed, and the accuracy of tasks across different noise conditions. These correlation coefficients indicate the degree of linear relationship between noise sensitivity and task load, task completion, and task accuracy.

Table 7: correlation calculation of four conditions

Condition	Correlation: Noise Sensitivity vs. NASA Task Load Index	Correlation: Noise Sensitivity vs. Amount of Task Completed	Correlation: Noise Sensitivity vs. Accuracy of the Task
38 dBA	0.63	-0.48	-0.33
38 dBA with speech	0.68	-0.86	-0.44
50 dBA	0.72	-0.84	-0.67
50 dBA with speech	0.74	-0.85	-0.19

Here are the correlation matrices for the four noise conditions. Every matrix displays the correlation coefficients between noise sensitivity and the metrics: NASA Task Load Index, accuracy of the task, and the amount of task completed under each specific condition.This highlights the varying degrees of correlation under various conditions. It also provides support for the explanation of how noise sensitivity affects perceived workload and performance outcomes in various noise environments.

Table 8. correlation matrix for 38 dBA condition

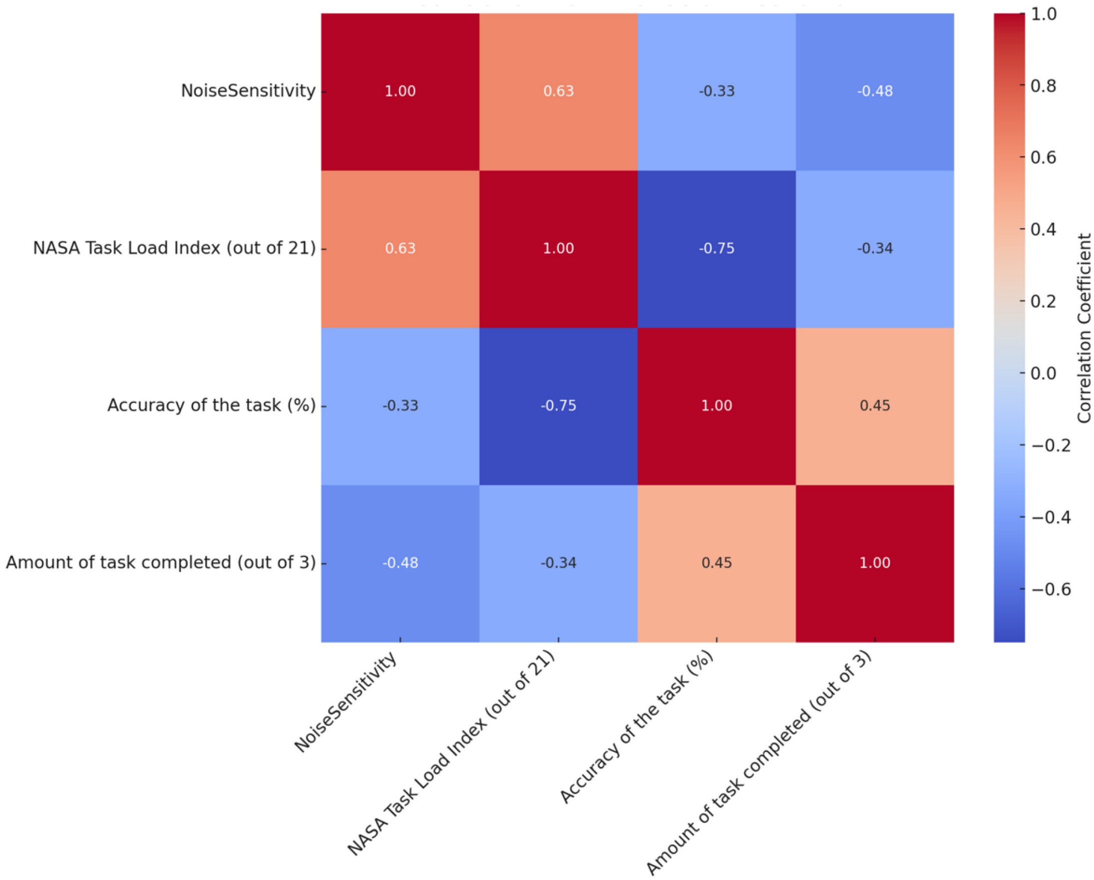


Table 9. correlation matrix for 38 dBA with speech condition

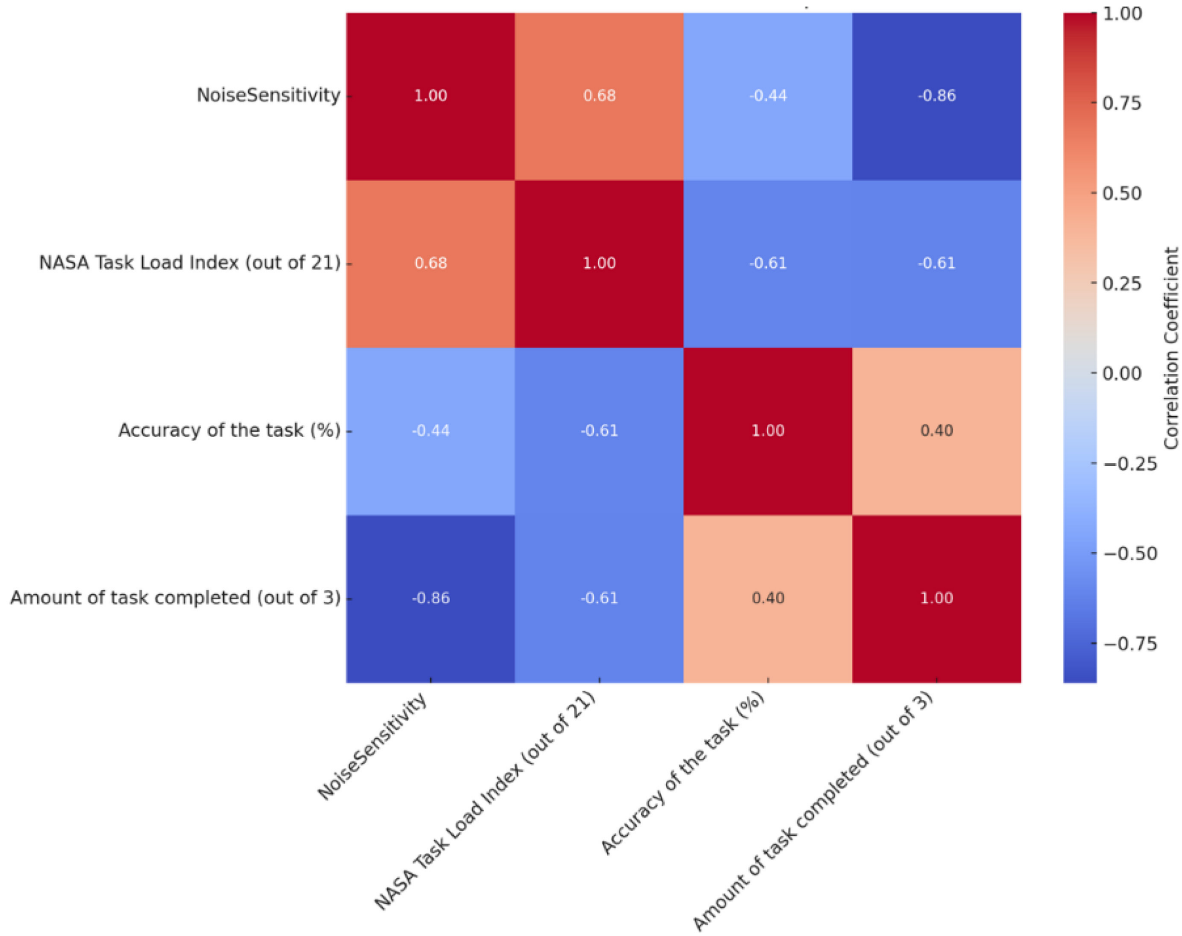


Table 10. correlation matrix for 50 dBA condition

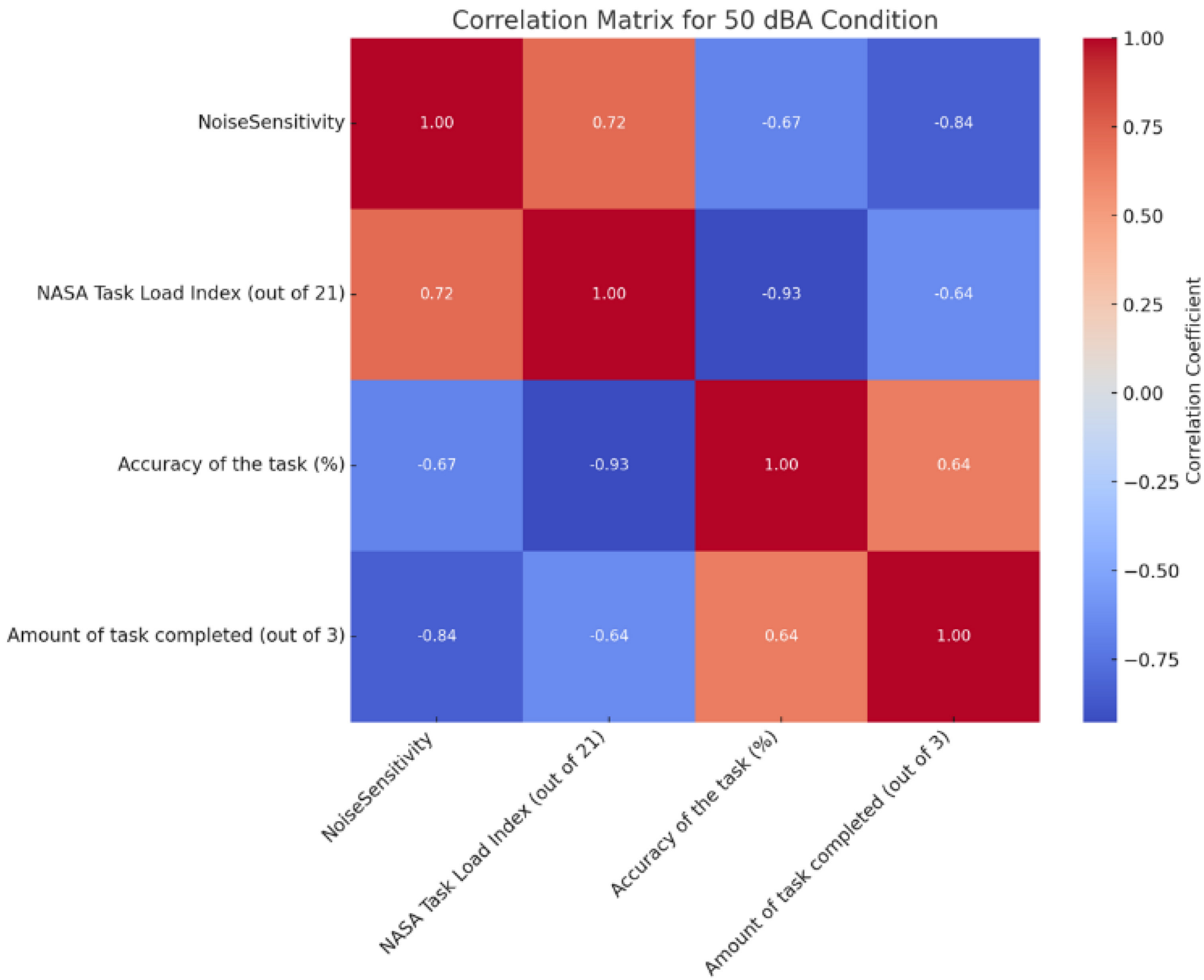
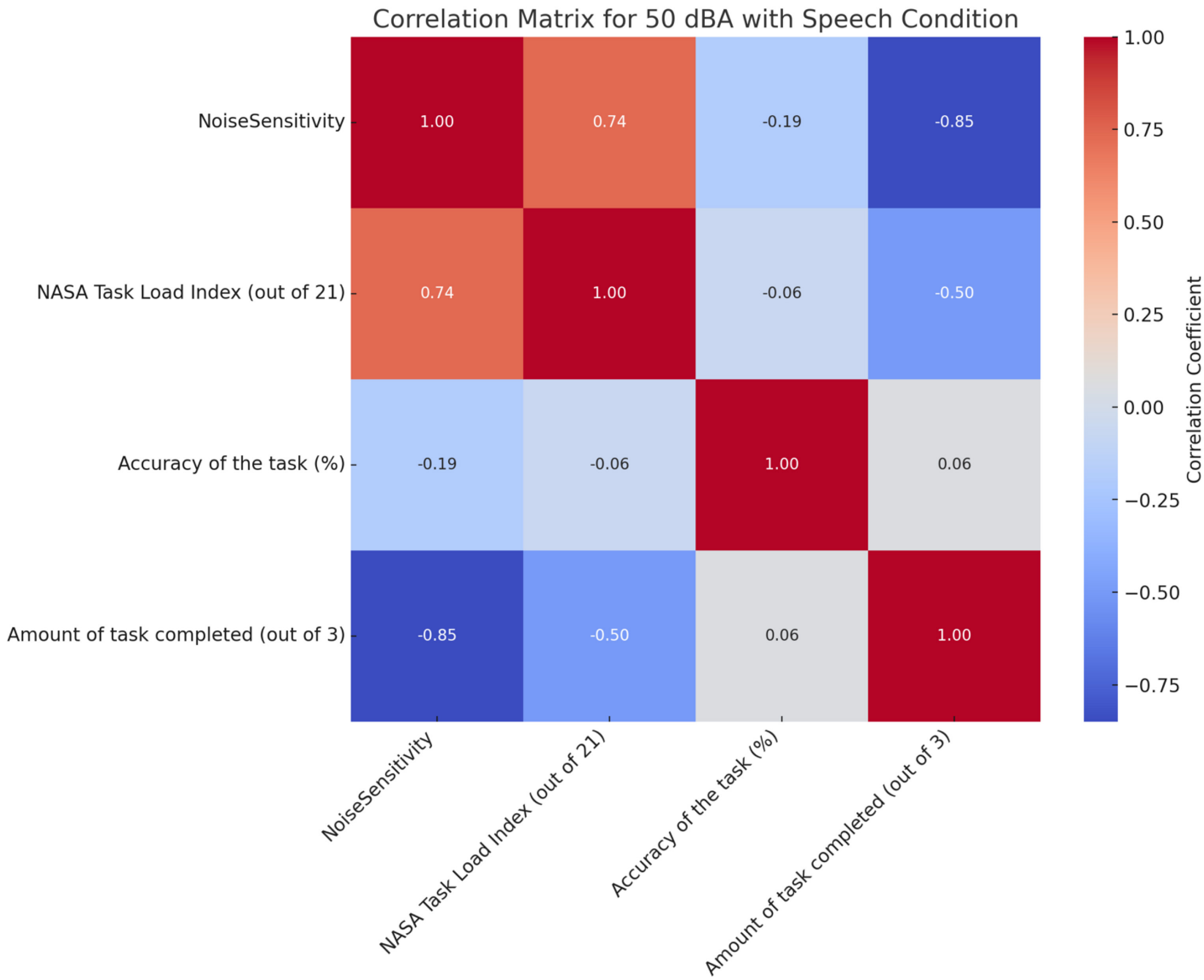


Table 11.correlation matrix for 50 dBA with speech condition



These correlations above provide insight into how noise sensitivity affects perceptions of task load and actual performance outcomes in noisy environments. In noise environments of 38 dBA with speech and 50 dBA with speech, the correlations between noise sensitivity and task load index were 0.68 and 0.74 respectively. This means that at higher noise levels (50 dBA with speech), participants' perception of task load increased slightly. On the other hand, in noise environments of 38 dBA and 50 dBA, the correlations between noise sensitivity and task completion were -0.86 and -0.85 respectively. This situation suggests that people's perception of task completion shows little change whether at lower or higher noise levels. Finally, the correlations between noise sensitivity and task accuracy were -0.44 and -0.19 in noise environments of 38 dBA with speech and 50 dBA with speech, respectively. This circumstance means that at higher noise levels, perceptions of task accuracy may decline, but to a smaller extent. In summary, people's perception of task load slightly increases in noise environments of 38 dBA and 50 dBA. Perceptions of task completion remain essentially the same, while perceptions of task accuracy may decline slightly, but to a smaller extent.

The correction matrix shows that noise sensitivity has a progressively increasing negative impact on workload perception and task performance of those participating in the experiment as the environmental noise level and complexity (presence of speech) increase a little bit. A moderate to strong positive correlation exists between noise sensitivity and the NASA task load index under all the conditions. This situation suggests that individuals with higher noise sensitivity experience greater workload and stress, especially in noisy environments or environments involving speech. The results also show that higher noise sensitivity was associated with less amount of task completion. Besides, effects on task accuracy were less consistent across conditions. In all conditions except the 50 dBA with speech condition, there is a significant negative correlation between accuracy and NASA task load index. This circumstance indicates that task accuracy decreases as task complexity or mental load increases in most cases.

4.3. summary

The presence of speech in the experiment introduces additional cognitive processing demands on the person while they are working on something projects. Similarly, an increase in noise levels causes the attention and cognitive abilities of participants to be more dispersed, further increasing cognitive load. This development highlights the compounding effects that noise, especially when combined with speech, can have on cognitive tasks. The presence of speech and noise not only increases cognitive difficulty but also increases variability in responses between participants. This variability may indicate differences in individual sensitivity or ability to filter out speech and noise, highlighting the effects of speech and noise on humans' cognitive load.

The worst data results occur in noisy environments with speech, indicating that this environment is the least conducive to tasks requiring concentrated cognition and attention. On the other hand, environments with lower noise levels and no speech, which are relatively quieter, provide more favorable conditions for cognitive performance and feelings of happiness. These detailed correlations across different noise and speech conditions illustrate the differential impact of environmental factors on individual sensitivity to noise. In conclusion, this data analysis provides acoustic design guidelines for understanding how environmental noise and speech interact with individual noise sensitivity to affect cognitive workload in open-plan offices.

5. Conclusion

5.1. Summary

The experiment was exposed to four different noise conditions, trying to mimic the atmosphere of a normal, everyday open plan office. Data collection took place in a controlled laboratory environment, with each participant completing tasks individually in a booth of university. The purpose of the survey for participants was to collect their perceptions of the four different types of noise experienced during the study. The research method included recruiting participants, explaining the procedure via PowerPoint, signing to obtain informed consent, participants performing common computing tasks under noise conditions, removing unreasonable data, and analyzing the collected data. In the four different acoustic environments, this study examined the impact of different typical sound source types and sound pressure levels on cognitive work.

Based on the experimental data, it can easily be concluded that noise sensitivity significantly affects perceived task load and actual task performance in four auditory environments, and that Speech and higher decibel levels amplify these effects. Participants who have been exposed to irregular noise environments for a long time may be sensitive to some sound changes. Some people who are exposed to irregular noise environments for long time may find it more challenging to adjust to the constant background noise produced by sound masking systems in open plan Offices. Continuous background noise from sound masking systems may exacerbate this sensitivity, heightening employees' discomfort and reducing some ability of working. The sound masking noise may not reduce disturbance from other noises, but it may increase some burden on employees working effectivity in the open plan offices. Sadly, irregular noise can easily trigger a stress response and reflection, especially when they think the noise as a threatening sound. The constant background noise from a sound masking system may exacerbate this stress response, as some people in the offices may consider the background sounds of a sound masking system as a source of noise pollution rather than a useful masking tool of open plan offices. The conclusion of this study is that before implementing any noise control measures in the open plan offices, the specific characteristics of the environmental issues and personal sensitivities of employees and employers must be assessed to ensure the effectiveness and suitability of the measures. When some employees feel that the background sound of the sound masking system is annoying and uncomfortable, it may be more appropriate to use other adaptive noise control technology that can adjust the sound masking level according to the constantly changing noise environment. However, when considering situations such as different types of noise and speech characteristics (e.g. volume, pitch) in the offices, it is very possible to get the different results, data and conclusion.

Designers for architecture and acoustic design should consider noise sensitivity as an important factor in sound design of workplaces, especially in tasks and job responsibilities requiring high levels of concentration or precision. These findings and results pave the way for the further research into how different types of noise and speech characteristics (such as volume, pitch) used in sound masking systems impact subtle differences in cognitive load. Additionally, this study illustrates the interpretations and insights derived from the data, providing valuable data conclusions and actionable information for future research efforts.

5.2. Limitations

It is important to acknowledge some limitations of this study. Firstly, the small sample of this research consisted of a convenience sample from the local community of Concordia University, Montreal, Quebec, Canada, which may limit the generalizability of the findings and the analyzes.

Secondly, the study's reliance on self-report measures for noise perception in the open space office is restricted to potential biases, which leads to not get the complete range of participants' experiences. It is common to know that self-report measures rely on individual perspectives that may vary.

Thirdly, virtual reality systems usually focus mainly on visual and auditory perception. The goal of VR environments is to immerse users in a computer-generated world. To achieve this goal, all human sensory systems theoretically need to be stimulated in a natural way. Since the visual system and sound stimuli are considered to be the main sources of information in human perception, much of the focus has been on these two areas [23]. While the simulation of other senses, especially touch and skin sensations, is relatively limited. No tactile experience during the experiment may lead to human perception bias.

Fourth, cultural differences and individual differences of human beings may affect the accuracy and reliability of the data and results. Different cultural backgrounds may greatly affect participants' understanding of and responses to experimental tasks or sound. Individual differences involve individual differences in cognition, emotion, and behavior may also lead to different understanding of subjective consciousness.

5.3. Future study

It is a good try to use a virtual reality device to perform the testing in a controlled setting at the acoustic lab of Concordia University. However, there are certain differences between the images of virtual reality headsets (like Oculus Quest 2 used in the current study) and the real world, including resolution, color reproduction and other factors. All the differences lead to the use of a Virtual Reality environment may not fully replicate real-life office conditions. This kind of difference may have an impact on the perception of sound for participants. The Oculus Quest 2 weighs 503g (17.7oz) [53]. Its inherent weight is quite heavy for human beings. Wearing it for 20 minutes is likely to result in head fatigue and a sense of heaviness. The sense of constraint from the head-worn device may make users feel restricted in their head movements, even in situations where free head movement is not necessary.

Therefore, virtual reality systems require great continuous improvements in the simulation of images to more accurately repeat the real world. Higher-resolution displays, more realistic rendering of environments, and more advanced audio technology, and more improved ergonomic design for Virtual Reality devices will all contribute to more valuable and precise data to be analyzed in effects of sound masking noise in the future.

Future research could also consider incorporating objective measures. Taking into account the potential impact of sound masking noise on office workers' comfort, work efficiency, and well-being, additional variables like absorption coefficient, reflection coefficient and transmission coefficient of floor, wall and ceiling can be contributed to further enhance the design of the study.

Additionally, HVAC noise will probably provide a more comprehensive understanding of the acoustic environment of open space offices. According to a report titled "Temperature Wars: Savings vs. Comfort" by the International Facility Management Association (IFMA), the second most prevalent HVAC complaints include issues such as "too drafty" and "too noisy." The noise of HVAC systems like heating, ventilation, and air conditioning systems may play a significant role in the overall acoustic experience of workers [54]. The interaction of ambient mechanical sounds with other acoustic elements in the open space office is an important aspect to consider for the researchers in future study.

References

[1] "Open Office Vs Closed Office Space – What Are the Pros and Cons?," Exis Global, 2024. [Online]. Available: https://www.exisglobal.com/open-office-vs-closed-office-space-what-are-the-pros-and-cons/.

[2] "What is Sound Masking?," Office Privacy, 2024. [Online]. Available: https://officeprivacy.com/pages/sound-masking-the-harmonic-solution-to-a-loud-problem.

[3] "What is Sound Masking? How does it work?," Resonics 2024. [Online]. Available: https://resonics.co.uk/what-is-sound-masking/#FAQs.

[4] A. K. H. L. S. M. M. Z. A. M. A. Shafaghat, "Open Plan Office Design Features Affecting Staff's Health and Well-being Status," p. 6, 2014.

[5] T. D. S. Debabrata Manna, "Achieving acoustic comfort in the library: a sound masking initiative," *Library Hi Tech News,* no. 14 May 2024.

[6] "Sound Masking and Speech Privacy Services," CABLIFY, 2024. [Online].

[7] "What is Sound Masking?," Cie-group, 2024. [Online].

[8] N. Moeller, "Tuning into Sound Masking," HPB HIGH PERFORMING BUILDINGS, 1 11 2016. [Online]. Available: https://www.hpbmagazine.org/tuning-into-sound-masking/.

[9] "OFFICE SOUND MASKING," Vibra-Sonic Control, 2024. [Online].

[10] R. Florence, "What is Sound Masking and How Does it Work?," Proacoustics, 25 April 2022. [Online]. Available: https:/www.proacousticsusa.com/blog/post/what-is-sound-masking-and-how-does-it-work-sound-masking-defined/.

[11] "Sound Masking 101," cambridgesound, [Online]. Available: https://cambridgesound.com/learn/sound-masking-101/.

[12] F. W. S. P. E. S. M. V. T. K. Abhishek Sahai, "Interactive simulation of aircraft noise in aural and visual virtual environments," *Applied acoustics,* pp. 24-38, 2016.

[13] K.B.Ginn.M.Sc, ARCHITECTURAL ACOUSTICS, DENMARK, 1978.

[14] A. Zola, "sound wave," Techtarget, June 2022. [Online]. Available: https://www.techtarget.com/whatis/definition/sound-wave#:~:text=A%20longitudinal%20wave%20is%20one,also%20include%20compressions%20and%20rarefactions..

[15] M. Long, Architectural Acoustics, 2014.

[16] A. Porteous, Dictionary of Environmental Science and Technology, 4th Edition, 2008.

[17] uvex-safety, "What is noise-induced hearing loss (NIHL)?," [Online]. Available: https://www.uvex-safety.co.uk/en/noise-induced-hearing-loss/.

[18] J. Sauer, "Acoustic Virtual Reality: An introductory research for application," 2020.

[19] F. a. J. F. Pausch, "MobiLab–A mobile laboratory for on-site listening experiments in virtual acoustic environments," *Acta Acustica united with Acustica 105, no. 5,* pp. 875-887, 2019.

[20] R. Bushey, "Advancements in Virtual Reality Device Development," rdworld, 11 September 2017. [Online]. Available: https://www.rdworldonline.com/advancements-in-virtual-reality-device-development-2/.

[21] M. Vorländer, "From acoustic simulation to virtual auditory displays," *Proc 22nd Int Congr Acoust ,* 2016.

[22] A. M. I. a. M. V. Heimes, "A real-time virtual reality building acoustic auralization framework for psychoacoustic experiments with contextual and interactive features," *Universitätsbibliothek der RWTH Aachen,* 2019.

[23] I. T. W. K. T. L. a. M. V. Assenmacher, "Integrating Real-time Binaural Acoustics into VR Applications," *In EGVE, vol. 4, pp. 8-9,* 2004.

[24] P. A. L. B. W. B. a. J. D. R. Bahadoran, "FXive: investigation and implementation of a sound effect synthesis service," *In International Broadcasting Convention (IBC),* 2018.

[25] Unity, "Unity," Unity, [Online]. Available: https://unity.com/.

[26] R. A. University, "virtualacoustics," RWTH Aachen University, [Online]. Available: https://www.virtualacoustics.org/.

[27] M. V. Anne Heimes, "A framework to conduct psychoacoustic experiments in virtual reality," *Tagungsband - DAGA 2021,* 2021.

[28] P. F. S. J. B. M. K. M. F. J. V. M. Aspöck L, "Application of virtual acoustic environments in the scope of auditory research," *Proceedings of XXVIII Encontro da Sociedade Brasileira de Acústica,* 2018 .

[29] A. L. P. P. F. J. V. M. Schaefer P, "A real-time auralization framework for scientific experiments," *The Journal of the Acoustical Society of America 154, no. 4_supplement ,* pp. A256-A256, 2023.

[30] sketchup, "sketchup," sketchup, [Online]. Available: https://www.sketchup.com/en.

[31] autodesk, "autocad," autodesk, [Online]. Available: https://www.autodesk.com/ca-en/products/autocad/overview?term=1-YEAR&tab=subscription&plc=ACDIST.

[32] T. I. A. M. V. a. T. K. Lentz, "Precise near-to-head acoustics with binaural synthesis," *JVRB-Journal of Virtual Reality and Broadcasting 3, no. 2 ,* 2006.

[33] P. a. A. B. Salamé, "Noise, unattended speech and short-term memory," *Ergonomics 30, no. 8 ,* pp. 1185-1194, 1987.

[34] H. J. T. R. V. M. Schlittmeier SJ, "The impact of background speech varying in intelligibility: Effects on cognitive performance and perceived disturbance.," *Ergonomics, 51(5),* pp. 719-736, 2008.

[35] W. M. F. J. Martin RC, "Reading comprehension in the presence of unattended speech and music," *Journal of memory and language, 27(4),* pp. 382-398, 1988.

[36] D. M. C. M. a. J. P. Jones, "Disruption of proofreading by irrelevant speech: Effects of attention, arousal or memory?," *Applied Cognitive Psychology, 4(2),* pp. 89-108, 1990.

[37] M. Leddy, "The biological bases of speech in people with Down syndrome," *Improving the communication of people with Down syndrom,* pp. 61-80, 1999.

[38] L. E. a. C. L. N. Smith, "International intelligibility of English: Directions and resources," *World Englishes 4, no. 3,* pp. 333-342, 1985.

[39] M. T. F. MTF, "Measuring Speech Intelligibility Using DIRAC—Type 7841".

[40] P. Jianxin, "Chinese speech intelligibility at different speech sound pressure levels and signal-to-noise ratios in simulated classrooms," *Applied Acoustics 71,* vol. no. 4 , pp. 386-390, 2010.

[41] A. L'Espérance, A. Boudreau, F. Gariépy, L.-A. Boudreault and R. Mackenzie, "Adaptive Volume Control for Sound Masking Systems: How It Works and Analysis of Performance," *INTER-NOISE and NOISE-CON Congress and Conference Proceedings,* vol. 254, pp. 678-686, 2017.

[42] T. R. Horrall, "Speech Privacy Systems:," [Online]. Available: https://cambridgesound.com/wp-content/uploads/2014/05/Speech-Privacy-Systems-Above-or-In-Ceiling_Web.pdf.

[43] "Audiology Room," eckelacoustics , [Online]. Available: https://eckelacoustics.com/audiology/audiology-room/.

[44] D. R. S. P. E. W. R. A. H. J. G. N. &. R. S. McCloy, "The UW/NU Corpus. Version 1.0.," 2013. [Online]. Available: https://depts.washington.edu/phonlab/projects/uwnu.php.

[45] E. H. C. W. D. G. N. H. M. H. L. N. K. S. S. H. R. U. G. E. &. W. M. Rothauser, "IEEE recommended practice for speech quality measurements," *IEEE Transactions on Audio and Electroacoustics,* vol. 17, p. 225–246, 1969.

[46] "BK CONNECT - MODULAR ANALYSIS SOFTWARE," BK CONNECT, [Online]. Available: https://www.bksv.com/en/analysis-software/data-acquisition-software/bk-connect.

[47] canadasafetycouncil, "Office Noise and Acoustics," [Online]. Available: https://canadasafetycouncil.org/office-noise-and-acoustics/.

[48] D. L. Worthington, "Weinstein Noise Sensitivity Scale (WNSS) (Weinstein, 1978)," in *The sourcebook of listening research: methodology and measures*, 2017, pp. 475-481.

[49] D. a. O. S. Ganor-Stern, "ADHD and math-The differential effect on calculation and estimation," *Acta Psychologica 188,* pp. 55-64, 2018.

[50] P. S. L. A. a. N. A. M. Kozulin, "Effects of a head-mounted display on the oculomotor system of children," *Optometry and Vision Science 86, no. 7 ,* pp. 845-856, 2009.

[51] S. G. a. L. E. S. Hart, "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research," *Advances in psychology,* vol. 523, pp. 139-183, 1988.

[52] S. G. Hart, "NASA-task load index (NASA-TLX); 20 years later," *Proceedings of the human factors and ergonomics society annual meeting,* vol. 50, pp. 904-908, 2006.

[53] M. A. Mavrinac, "Oculus Quest 2 Specifications," [Online]. Available: https://studiox.lib.rochester.edu/oculus-quest-2-specifications/.

[54] "IFMA study examines office temperature complaints, FM responses," [Online]. Available: https://www.fmlink.com/articles/ifma-study-examines-office-temperature-complaints-fm-responses/.

[55] M. Vorländer, "From acoustic simulation to virtual auditory displays," *Proc 22nd Int Congr Acoust,* 2016.

Appendix A: Sequence of Experimental Conditions

	Condition for the first attempt	**Condition for the second attempt**	**Condition for the third attempt**	**Condition for the fourth attempt**
1	3	4	2	1
2	3	4	1	2
3	4	2	1	3
4	4	1	2	3
5	3	1	4	2
6	1	3	4	2
7	2	4	3	1
8	4	3	2	1
9	2	4	1	3
10	2	1	4	3

The first condition: 38 dBA (pink noise)

The second condition: 50 dBA (pink noise)

The third condition: 38 dBA (pink noise) with a speech signal at 53 dBA

The fourth condition: 50 dBA (pink noise) with a speech signal at 53 dBA

Appendix B: Detailed calculations employed in the VR tasks

	Calculations	One fifth of the exact answer	Five times the exact answer	One half of the exact answer	Twice the exact answer
1	87x9 =	157	3915	392	1566
2	98x8 =	157	3920	392	1568
3	99x8 =	158	3960	396	1584
4	89x9 =	160	4005	401	1602
5	94x9 =	169	4230	423	1692
6	93x9 =	167	4185	419	1674
7	88x9 =	158	3960	396	1584
8	86x9 =	86	2150	215	860
9	95x9 =	171	4275	428	1710
10	88x9 =	158	3960	396	1584
11	96x8 =	154	3840	384	1536
12	98x9 =	176	4410	441	1764
13	99x9 =	139	3465	347	1386
14	96x9 =	173	4320	432	1728
15	90x9 =	162	4050	405	1620
16	91x9 =	91	2275	228	910
17	92x9 =	110	2760	276	1104
18	97x8 =	155	3880	388	1552
19	97x9 =	175	4365	437	1746

20	85x9 =	153	3825	383	1530
21	84x8 =	134	3360	336	1344
22	83x6 =	100	2490	249	996
23	82x7 =	115	2870	287	1148
24	81x6 =	97	2430	243	972
25	80x9 =	144	3600	360	1440
26	69x5 =	69	1725	173	690
27	42x8 =	67	1680	168	672
28	37x3 =	22	555	56	222
29	23x6 =	28	690	69	276
30	17x5 =	17	425	43	170
31	39x2 =	16	390	39	156
32	46x1 =	9	230	23	92
33	14x9 =	25	630	63	252
34	28x7 =	39	980	98	392
35	12x4 =	10	240	24	96
36	33x3 =	20	495	50	198
37	88x10 =	176	4400	440	1760
38	87x11 =	191	4785	479	1914
39	86x12 =	206	5160	516	2064
40	85x13 =	221	5525	553	2210
41	84x14 =	235	5880	588	2352
42	83x15 =	249	6225	623	2490

43	82x16 =	262	6560	656	2624
44	81x17 =	275	6885	689	2754
45	80x18 =	288	7200	720	2880
46	79x19 =	300	7505	751	3002
47	78x20 =	312	7800	780	3120
48	77x21 =	323	8085	809	3234
49	76x22 =	334	8360	836	3344
50	75x23 =	345	8625	863	3450
51	74x24 =	355	8880	888	3552
52	73x25 =	365	9125	913	3650
53	72x26 =	374	9360	936	3744
54	71x27 =	383	9585	959	3834
55	70x28 =	392	9800	980	3920
56	69x29 =	400	10005	1001	4002
57	68x30 =	408	10200	1020	4080
58	67x31 =	415	10385	1039	4154
59	66x32 =	422	10560	1056	4224
60	65x33 =	429	10725	1073	4290
61	64x34 =	435	10880	1088	4352
62	63x35 =	441	11025	1103	4410
63	62x36 =	446	11160	1116	4464
64	61x37 =	451	11285	1129	4514
65	60x38 =	456	11400	1140	4560

66	59x39 =	460	11505	1151	4602
67	58x40 =	464	11600	1160	4640
68	57x41 =	467	11685	1169	4674
69	56x42 =	470	11760	1176	4704
70	55x43 =	473	11825	1183	4730
71	54x44 =	475	11880	1188	4752
72	53x45 =	477	11925	1193	4770
73	172x37 =	1273	31820	3182	12728
74	121x65 =	1573	39325	3933	15730
75	276x27 =	1490	37260	3726	14904
76	308x18 =	1109	27720	2772	11088
77	181x43 =	1557	38915	3892	15566
78	123x64 =	1574	39360	3936	15744
79	153x32 =	979	24480	2448	9792
80	142x19 =	540	13490	1349	5396
81	129x37 =	955	23865	2387	9546
82	299x24 =	1435	35880	3588	14352
83	357x21 =	1499	37485	3749	14994
84	408x20 =	1632	40800	4080	16320
85	443x18 =	1595	39870	3987	15948
86	504x16 =	1613	40320	4032	16128
87	523x15 =	1569	39225	3923	15690
88	601x11 =	1322	33055	3306	13222

89	628x13 =	1633	40820	4082	16328
90	572x14 =	1602	40040	4004	16016
91	246x30 =	1476	36900	3690	14760
92	101x77 =	1555	38885	3889	15554
93	111x12 =	266	6660	666	2664
94	222x13 =	577	14430	1443	5772
95	330x14 =	924	23100	2310	9240
96	109x15 =	327	8175	818	3270
97	211x16 =	675	16880	1688	6752
98	155x17 =	527	13175	1318	5270
99	166x 18	598	14940	1494	5976
100	133x19 =	505	12635	1264	5054
101	144x20 =	576	14400	1440	5760
102	180x21 =	756	18900	1890	7560
103	190x22 =	836	20900	2090	8360
104	107x23 =	492	12305	1231	4922
105	135x24 =	648	16200	1620	6480
106	126x25 =	630	15750	1575	6300
107	140x26 =	728	18200	1820	7280
108	150x27 =	810	20250	2025	8100

Appendix C: NASA Task Load Index

Note: Performance goes from good on the left to bad on the right.

Mental Demand: How mentally demanding was the task?

Very Low | Very High

Physical Demand: How physically demanding was the task?

Very Low | Very High

Temporal Demand: How hurried or rushed was the pace of the task?

Very Low | Very High

Performance: How successful were you in accomplishing what you were asked to do?

Perfect | Failure

Effort: How hard did you have to work to accomplish your level of performance?

Very Low | Very High

Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low	**Very High**