“Binauralize Your Beats”

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Tucker Alexander, Duncan Hanson, Mir Jeffres, Kai White

Context

Beat frequencies are the results of wave interference. When two frequencies that are close together are played at the same time, the two waves will constructively and destructively interfere to create a “beat”, which has frequency |f2-f1|. To create binaural beats, a listener wears headphones, and each ear receives one of two close frequencies. The beats are not physically present in the air, as the waves only go into the listener’s ears, but they are created in the brain as it processes the two inputs. These binaural beats have been proven to affect brain activity and potentially mood. A binaural beat frequency’s effect corresponds with the five widely recognized brain wave frequency bands: Delta (0.5-4 Hz), Theta (4-8 Hz), Alpha (8-12 Hz), Beta (12-30 Hz), and Gamma (30-44 Hz). Delta waves are dominant in sleep, theta waves are dominant while deeply relaxed and focused inwards, alpha waves are dominant when very relaxed and calm, beta waves are dominant when attention is focused, and gamma waves are dominant when processing information.

The use and efficacy of binaural beats fall under brain entrainment, the manipulation of brain waves based on the notion that the human brain is capable of altering its own waves and frequencies based on the rhythms of external stimuli. Utilizing these patterns allows for the altering of mental and physical states, as suggested by the myriad research done on the effects. A 2020 study sought to identify a link between the use of binaural beats and chronic pain with the thought that brain entrainment could alter subjects’ perceptions of their pain and thus reducing their need for analgesic pain medications. The researchers found that the use of a beat frequency of 5 Hz (in the theta range) reduced subjects’ pain intensity and use of analgesics when compared to subjects who were exposed to blank tapes (Gkolias et al.). Similarly, a 2017 study sought to identify the effects of binaural beats on the stress response of military service members with post-deployment stress. Service members who reported post deployment stress were exposed to stressors, with some subjects having used a combination of music and binaural beats in the theta range and others solely music. The study showed that there was a decrease in the sympathetic nervous response and an increase in the parasympathetic nervous response in subjects who used the binaural beats (Gantt et al.). Many studies have been conducted with a focus on the effect that binaural beats have on attention and memory, with data supporting that the use of beats in the gamma frequency range increased focus on tasks as well as augmenting short term memory.

From a clinical standpoint, binaural beats have a wide range of potential utilizations. The use of theta waves on individuals with chronic pain could have an impact of a lowered risk of dependency on and abuse of analgesics and pain medications, with the use of binaural beats being a safe and low-cost supplementation for traditional pain management (Gkolias et al.). Additionally, while music alone is proven to be a useful tool for relieving stress for a lot of people, the use of binaural beats may be especially effective for those who have been exposed to high levels of stress in their lifetime (Le Scouarnec et al., 2001). Early intervention could also potentially diminish susceptibility to stress-related conditions such as posttraumatic stress disorder, anxiety, insomnia, substance abuse, and eating disorders. In addition to providing stress relief and reducing pain intensity, the use of binaural beats could support attention control in those with attentional disorders.

Motivation

There are few online tools to create binaural beats that explain each beat frequency's significance, and fewer (zero working examples) that can give already existing audio files a binaural beats component. This project aims to create a mental health and educational tool that can be used by anyone at any skill level to add binaural beats to music.

Applications

Binauralize your Beats is useful for anybody that enjoys music and wants to improve their mental well-being. Binaural beats have been shown to produce positive effects medically for listeners, and by adding binaural beats to a listener's own music, it can allow users to not only listen to their favorite music while they do things like study, sleep, and relax, but actually enhance their ability to perform those tasks. Students could add beta wave binaural beats to their own music while they study and improve memory retention (Garcia-Argibay, 2019). People who suffer from sleeping disorders could use theta and delta wave binaural beats to help induce and maintain sleep (Lee, 2019). Anybody trying to relax and listen to music could benefit from theta-wave binaural beats in order to reduce anxiety (Padmanabhan, 2005).

Related work, demonstration of need

There are a few apps and websites that offer binaural beat generation that users can customize the base and beat frequencies of, but there are no available apps or websites that offer generating binaural beats in music like what was proposed. There were two examples of applications that might have done this, called UBrain and SongRest, but they were both 5-10 years old and no longer publicly available. This tool aims to fill the gap in binaural beats accessibility by creating a website with capabilities to add a binaural beats component to the user's music, while also providing explanations and educational resources.

Below are some examples of preexisting binaural beat generators (one website and one mobile app). They just generate tones with binaural beats, nothing about combining music and binaural beats.
Harmonic Binaural Beat Brainwave Maker • Online & Free
Binaural Beats Generator + on the App Store

Goal

To create a website that can add two closely spaced frequencies in each ear to an existing song in order to create a binaural beating sensation with the bass for the purpose of reducing stress and anxiety, inducing sleep, or improving mood or long-term memory based on the user's desired health goals.

Software overview

The web application format minimizes the requirements and limitations of an app. Although slightly hindered by the fact that it only runs locally as of right now, the requirements and dependencies for the application are minimal. The Github repository for this project includes a very short "Requirements.txt" file with all the necessary dependencies for the application to run. If a user has Python installed on their computer they can easily download and run the application locally. Although there was an option to run the backend using a GPU, the researchers decided to make it a CPU-only application for greater accessibility.

The web app utilizes the Flask framework for hosting the back end Python server and front end HTML which utilizes Jinja2 templates and XHR requests to interface between the front and back end.

The back end of the application is built in Python, using extension libraries such as Demucs, SciPy, Numpy, and Librosa. The blockchain can be described in three main stages, with some filtering and other processing in between. The first step, after reading in the audio file, is to extract the bassline to be "binauralized". Demucs, a machine learning based source separation library, isolates the bassline, vocals, drums, and other audio sources in any audio file uploaded. In this project, Demucs is configured to use the "mdx_q" model for source separation, which is the quantized version of the highest-ranked model at the ISMIR MDX challenge. The quantized version was chosen to save memory and time on the first run of the binauralizer on any given computer. Even with a small machine learning model, according to Demucs documentation, Demucs takes around 1.5 times the length of the uploaded audio file to separate tracks when a computer's CPU is used. In practice with "Binauralize Your Beats", the time to separate the tracks is around 3 times the length of the original file. This may be due to Python or Flask's server speeds, there is likely a limit to the amount of CPU that can be used within a running server, and the site has only been tested locally. Once the webapp is ported to a remote web host, it may have more processing power allotted or a GPU, and so the binauralization script would take less time to run. After Demucs' lengthy processing, the isolated bass track is passed through a lowpass filter with high cutoff frequency. The filtering stage here is to remove extraneous noise inadvertently captured during source separation.

Stage two involves implementation of a frequency shifting function. The bassline must be shifted in frequency, either up or down, in one ear for the binaural beating sensation to occur. Utilizing a Hilbert transform to bring the time domain representation of the bassline into the frequency domain, simple multiplication of this signal with a desired frequency shift will apply the shift to the target audio. The Fourier Transform is a very commonly used option for mapping to the frequency domain, but this application uses the Hilbert Transform for one of its unique properties. The Hilbert Transform imparts a uniform phase shift on all frequencies, whereas the Fourier Transform will have a phase response that is frequency dependent. Since one of the aims of the application is to maintain audio quality as much as possible, a uniform phase response of the function minimizes unwanted artifacts in the final signal. After shifting, the data is brought back to time domain representation via Inverse Hilbert Transform.

Stage three can be thought of as gluing the whole thing together. The original audio, the isolated bassline, and the frequency shifted bassline are all now saved as time series information. To create a stereo signal, the left channel is set to be the sum of the original audio and the original bassline, and the right channel is the sum of the original audio with the shifted bassline. This is beneficial because it maintains the audio quality of the original recording while also injecting a subtle binaural beating effect, which is the goal.

The frontend of this tool consists of three pages with which the user will interact: the landing page, upload page, and educational page. The landing page consists of five buttons to represent the frequency bands which the desired beat frequency will fall under. The buttons are presented as a choice. The upload page contains the dropdown bar that communicates with the backend and sets the frequency with which the backend processes the uploaded audio file. The educational page is designed to give a basic understanding of binaural audio and the effects it has over the brain's wave state. The page has illustrations, graphs, text, and links to other studies in order to more effectively explain binaural beats to the user. The educational page also defines each brain wave frequency band, delta, theta, alpha, beta, and gamma waves, and how entraining the brain to those frequencies can produce medical benefits.

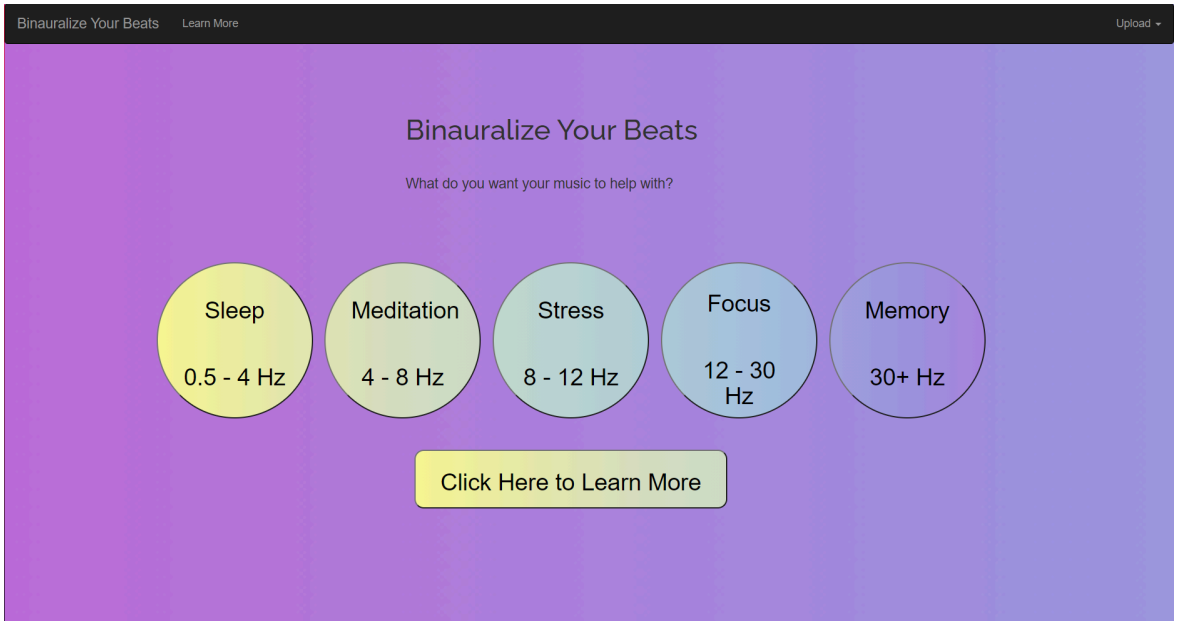
Installation/usage

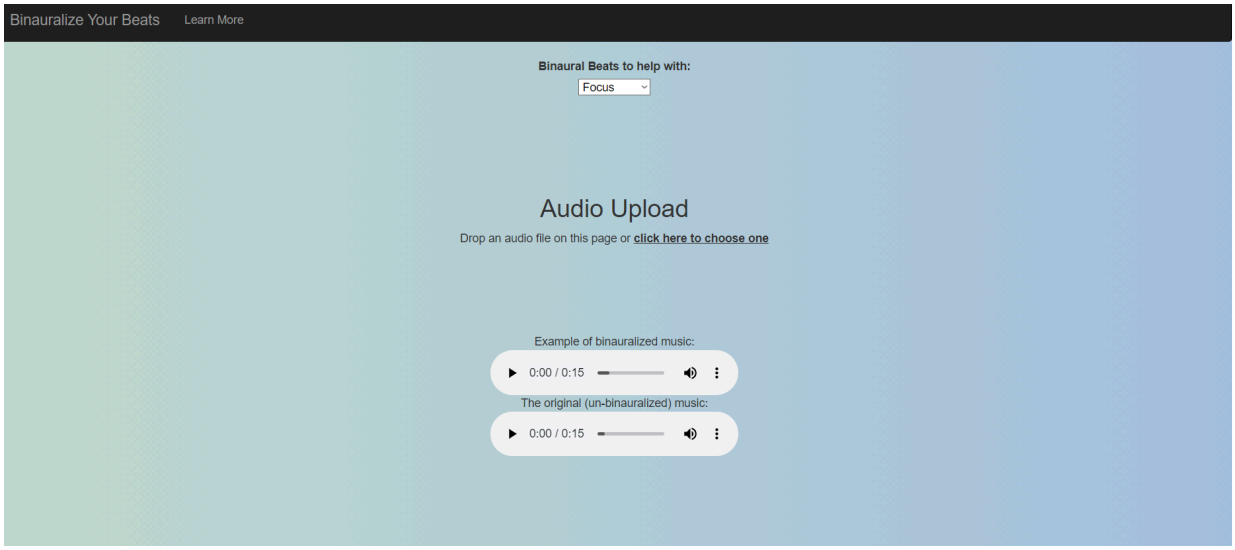
To run the website locally, clone into the GitHub repository, run "pip install -r requirements.txt" to install all the dependencies, and then run the Python script "song_upload_server.py" to start the Flask server and navigate to the localhost address given in the command line. The website loads to the landing page, where the user can select which health goal they desire (Sleep, Meditation, Stress, Focus, or Memory) or the "Learn Page" to learn more about binaural beats and the different brain waves. Clicking on a health goal takes the user to the "Upload Page" where they can listen to examples and then upload an audio file to be binauralized, which has binaural beats at frequencies depending on the currently selected option in the dropdown menu at the top of the screen. After processing, the outputted "binauralized" audio file will be located where the examples were, and can be played in the browser or downloaded for future listening and another audio file can be uploaded. The website is easy to navigate and understand, and the "Learn" page has an explanation of binaural beats that is applicable to people of any knowledge level.

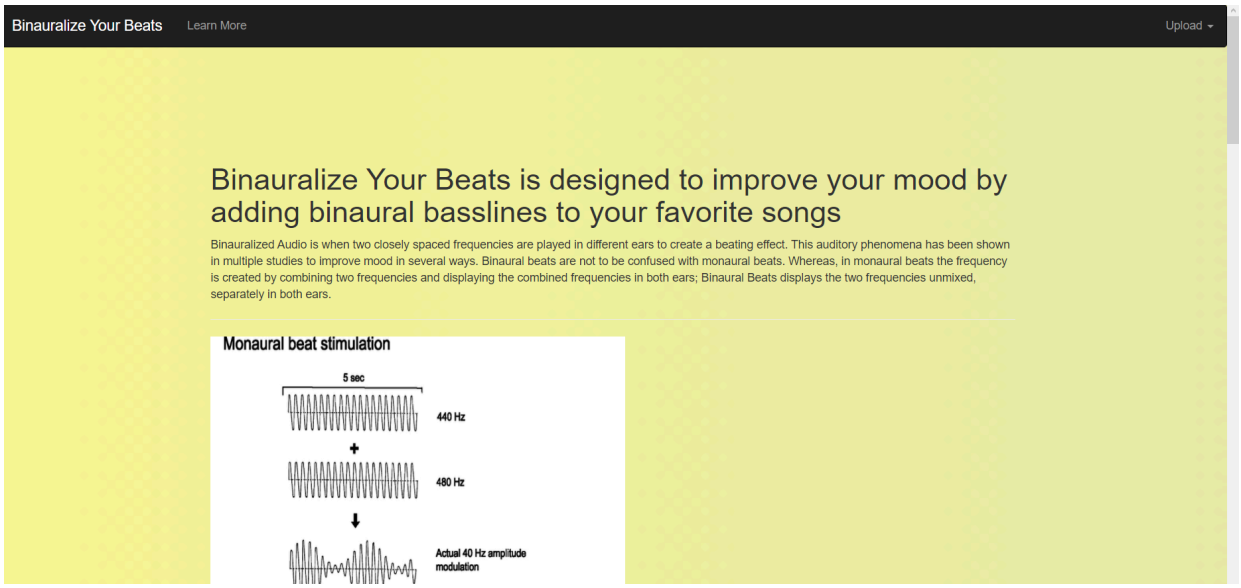
Limitations

Limitations of this website include that it is currently only locally hostable, so the user needs to know how to use the command line to run it. It also runs relatively slowly (~4x the length of the uploaded file to output the binauralized file), since it is using the computer's CPU and the back end of source separation and filtering takes a long time computationally. The speed may be increased Once the website is ported to a remote web hosting service with a larger CPU space allocation, the audio processing may get faster, but it will require an internet connection to run. Another limitation is in the formatting of the input audio files. Currently only .mp3 and .wav files are supported, and in the future the audio file capabilities can be expanded by increasing the number of file extensions supported as well as streaming service functionality; being able to choose any song on YouTube or Spotify would make binauralized music much more accessible.

Examples - Screenshots and audio example







Link to example audio files (binauralized files are called "bin_filename.wav"):
https://drive.google.com/drive/folders/1VLvUyFOBQtrKGbZAar5KqL6ICCmliEdR?usp=sharing

Evaluation

The software was evaluated based on the success had with "binauralizing" the uploaded audio as well as the efficacy of the education page. Our original goals were as follows:

1.) The website is easy to navigate and the content is explained well enough that anyone with an interest in the topic could understand
2.) The sound processing is not distracting to the user while creating the intended beating effect
3.) The site can pull music from a user-uploaded file and implement the desired binauralization

In regards to ease of navigation, the presence of a navigation bar that reflects how most websites are laid out nowadays, and the buttons showing the mental health goals which affect the frequency of the binaural

beats are clearly marked and labeled. The education page explains the beating phenomenon as well as the affected brain waves in a way that is understandable to those who have no exposure to the subject at large. With the “binauralization”, the upload functionality works, and the researchers have observed that the output audio does contain the intended beating phenomenon and is not distracting. In fact, in some informal user testing, feedback was given that the beats were too subtle at times. Luckily, it is possible to change the binaural beats’ volume in the back end code, and a slider can be implemented in the front end rather easily in the future.

Future work

The first and most important update that needs to be made to improve the application is giving it a permanent and public web domain. This could be done using Heroku, a platform that allows applications to be built and run in the cloud. This is important because as of right now, the most difficult part of using the application for a non-programmer is setting up a local server to run it on. Typing in a URL and having the site load would be much more user friendly. Another way to make the app more user friendly would be refactoring to decrease loading time. Demucs, unfortunately, is a very slow tool and takes approximately 1.5 times the length of the uploaded audio to separate the stems. This does not even include the time that it takes for Python to carry out frequency shifting and data structuring, as well as the time it takes for the back end and front end to communicate. Looking further into the documentation of Demucs could help minimize the wait times, as well as simply reworking the way the code is structured to make it more efficient. In terms of site functionality, the dropdown menu for selection of frequency band needs to be linked to the backend. Additionally, a volume selector or knob would be nice as a way of controlling the intensity of the binaural beating in the stereo mix. Allowing users to upload audio straight from YouTube or Spotify would also be a good direction to take, minimizing the work that users have to do to use the application. Finally, marketing for the application would be a good way to draw in new users and gain a following. Social media can be very powerful for this.

Critical reflection

Duncan: First, I had to research binaural beats and the different brain waves that it can entrain. I did have some experience with EEG signals in Dr. Leslie’s class, but not binaural beats. As for tools, I had never done any website front-end design which was my primary focus for this project, so I had to learn the basics of CSS, HTML, and JavaScript. If I could go back I would definitely try to figure out how to set up a grid using Bootstrap so I could organize the webpages a bit more.

Kai: Most of what I learned came from researching binaural beats since I’d had little exposure to them. I understood how the beating phenomenon worked fundamentally, but not within the context of brain entrainment. I’d also never done any web development prior to this, so I learned a lot about making a webpage work and referencing both CSS and JavaScript within the base HTML as well as creating templates for Flask to use.

Mir: Through working on the backend server side of this project, I learned about hosting websites with the Flask framework, and learned more about ways to deploy sites, deciding on Heroku as the final choice for future deployment. I also gained experience using XHR requests, as those are needed to send information from the front end to the back end with Flask (Flask is a one sided framework for information sending but not receiving). If I had to do this project again, I would have been more open to changing the

libraries we were using for the backend source separation. I spent several weeks attempting to make Spleeter work in the Flask site, but it kept crashing the site or my computer and so when I made the switch to Demucs, it only took an hour to get the site working again. However, through this process, I learned more about TensorFlow and exactly how Flask hosts Python servers.

Tucker: First and foremost, I learned the importance of preplanning when working on relatively wide-scoped projects like this. Among our confusion using various plugins and libraries, and trying to find what tools were best for our specific project, a lot of time ended up being wasted. For example, I spent a considerable amount of time trying to implement Librosa's pitch shifting function before realizing that this is a fundamentally flawed approach to our problem and that I needed to create a frequency shifting function instead using different libraries. This probably could have been avoided by more in depth planning of exactly what we want to do, including a comparison of all the possible tools at our disposal to accomplish these goals. Weighing all of our software options could have also helped with the Spleeter issue, as well as our troubles with Heroku that lead to our switching over to Flask. Problems are bound to pop up when working on projects like this but if we were able to go back and start over knowing what we know now, we would definitely weigh out all our software options and come up with a couple "backups" in case one doesn't work out as intended.

To organize the group, we began with using GroupMe to communicate and Trello for task management, and by the end of the semester, we were using Discord to communicate and discuss when tasks were completed. We stopped using Trello after the first few weeks once everyone had a specific task within the project, with Duncan and Kai working on front end and Tucker and Mir working on backend. Using Trello for project management the whole time would have streamlined our process and helped everyone finish their tasks earlier so we would have had time to implement more of our stretch goals. Discord worked better for our method of communication, as it has built in call capabilities and we had a separate channel to talk about progress updates. Our group management worked for this project's scope and time spent, but if we had to do it again, we would have integrated front and back end more often, as we ended up working on individual tasks independently for so long that we had to scramble to connect all the components the week before the project was due. Overall, we worked well together, planning meetings outside of class time throughout the semester to make more progress, and we are proud of how the website works according to our original goals. We plan to polish up the site more in the future and host it online using Heroku for anyone to use.

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