Tintinnabulist: A Pd-Based Educational Instrument for Harmony and Auditory Perception

I. INTRODUCTION

This report presents the conception and implementation of *Tintinnabulist*, an educational synthesis and psychoacoustic demonstration instrument developed in the Purr Data environment. It was undertaken in response to a brief from SynthAcademy Inc., aligned with the UK Government's "Electronics in Schools" initiative, which calls for pedagogical software aimed at sixth-form A-level Music Technology students. The assignment required the production of a unified system demonstrating both sound synthesis and auditory perception principles in an accessible, exploratory format.

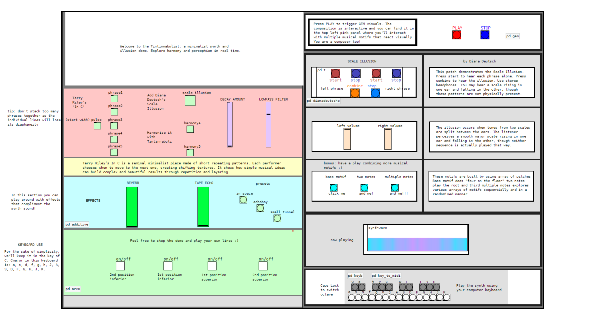


Fig. 1: Interface layout of the *Tintinnabulist* patch in Purr Data. The interface combines synthesis controls, psychoacoustic modules, and playback interaction in a unified educational workspace.

The patch developed meets this specification through two core features: a rule-based harmonic synthesiser rooted in additive synthesis, and a perceptual module based on Diana Deutsch's "mystery melody" illusion. The former allows for the real-time construction of tones from four harmonically related partials, each amplitude-scaled and dynamically enveloped. The latter employs ear-specific melodic streams to reveal perceptual grouping biases in melodic cognition. Originally formulated in 1972, Deutsch's illusion remains a seminal case study in the role of expectation, memory, and hemispheric lateralisation in melodic perception.

The instrument integrates a keyboard interface, dynamic parameter control, and real-time visualisation via GEM. Its harmony engine, adapted from Arvo Pärt's *tintinnabuli* technique, generates a companion voice according to modal position rules. This design enables learners to explore generative harmony through constraint-based logic while inspecting the underlying synthesis process.

The sections that follow present a technical account of the synthesiser's structure, psychoacoustic system, and user interface. Particular attention is paid to perceptual engagement, interface clarity, and the educational framing of audio parameters. Time- and frequency-domain analyses are provided where relevant, grounding perceptual phenomena in measurable signal descriptors.

II. INTRODUCTION TO THE SYNTHESISER

Additive synthesis is among the earliest formalised methods of sound construction. Its conceptual basis lies in Fourier analysis, wherein complex waveforms are understood as the summation of sinusoidal components. In the 1950s, electronic music laboratories in Cologne and Paris implemented additive techniques by layering sine waves from calibrated oscillators. Later, software environments such as Music V and hardware platforms like the Yamaha SY and DX series revived the method within digital architectures. While less prominent in commercial synthesis today, additive methods retain instructional value due to their analytical transparency and direct mapping between structure and timbre.

The synthesiser developed for this project adopts a four-partial architecture, whereby each MIDI input triggers six harmonically related sinusoids. These partials are amplitude-scaled and routed through a shared ADSR envelope before summation. The interface maps two chromatic octaves onto the computer keyboard, offering immediate playability and pitch control. Post-processing options, including reverb, tape delay, and decay modification, afford further shaping without occluding the spectral logic.

This structure supports timbral construction as an intentional act. By varying the relative amplitudes of partials, students can hear how brightness, warmth, and sharpness emerge from harmonic weighting. The instrument's affordances promote experimentation, comparison, and sonic inspection. These principles are foundational to any pedagogical tool in audio technology.

The synthesiser is further extended by a rule-based harmony module adapted from Arvo Pärt's *tintinnabuli* technique. This logic derives a second voice from the input note, calculated via intervallic displacement within a fixed modal system. Unlike spontaneous counterpoint, tintinnabuli enforces deterministic voice-leading rules, exposing harmonic dependency as an inspectable structure. By combining this logic with an additive engine, the instrument enables learners to explore both spectral and harmonic organisation within a controlled and intelligible system.

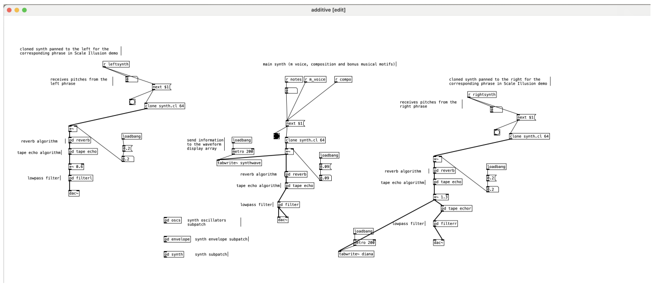


Fig. 2: Additive synthesis patch architecture showing modular signal routing. Three synthesiser clones (for left ear, right ear, and main voice) are fed MIDI input and routed through amplitude shaping, filtering, and visual display subsystems. Modular subpatches support clarity, reusability, and pedagogical inspection.

A. Pd Design Rationale

The patch was constructed with an emphasis on clarity of structure, modularity of function, and accessibility of logic. Each subsystem, including synthesis, harmony, signal processing, and control interface, is contained within its own subpatch. The main interface reflects these divisions through colour zoning and layout. The design invites inspection and facilitates adaptation, serving both as a working instrument and as a teaching object.

The graphical interface is divided into distinct zones. Phrase triggers and harmony controls occupy the upper red section. Effects controls are placed centrally in blue, while keyboard interaction and tintinnabuli toggles reside in the lower green segment. A psychoacoustic demonstration module, set apart in grey, completes the layout. Each region is annotated with concise instructional comments written for sixth-form learners encountering synthesis for the first time.

The primary sound engine is housed in `[pd additive]`, where four oscillators generate harmonic partials. Each `osc~` receives a frequency multiplier, producing detuned fundamentals, an approximate fifth, and a higher overtone, along with a corresponding amplitude coefficient. The partials are summed and routed through a simple attack-decay envelope implemented in `[pd envelope]` using `line~`. Decay time is user-adjustable. This signal then passes through a lowpass filter, granting additional timbral control.

Melodic input is facilitated by the subpatches `[pd keyb]` and `[pd key_to_midi]`, which map ASCII key values from the QWERTY keyboard to MIDI note numbers across two chromatic octaves. Octave transposition is toggled via the Caps Lock key. The layout is illustrated graphically on the main interface, enabling intuitive exploration without reference to external documentation.

Polyphony is achieved via the `clone synth.cl 64` object. Each incoming note message is assigned to an available voice using the `next $1` instruction, which provides reliable channel distribution under load. All voices are routed through the same processing chain with uniform access to reverb, delay, and filter modules. This configuration permits both live improvisation and algorithmic generation without constraint.

Harmonic extension is realised through four subpatches: `[pd 1inferior]`, `[pd 2inferior]`, `[pd 1superior]`, and `[pd 2superior]`. Each produces a tintinnabuli voice in real time based on positional rules. For pedagogical clarity, the system is restricted to C major. This decision reflects a desire to reduce cognitive overhead for learners unfamiliar with scale theory. Within each subpatch, MIDI notes are selected, transposed, and rerouted to dedicated synthesis instances. Each block is explicitly labelled and commented for ease of comprehension.

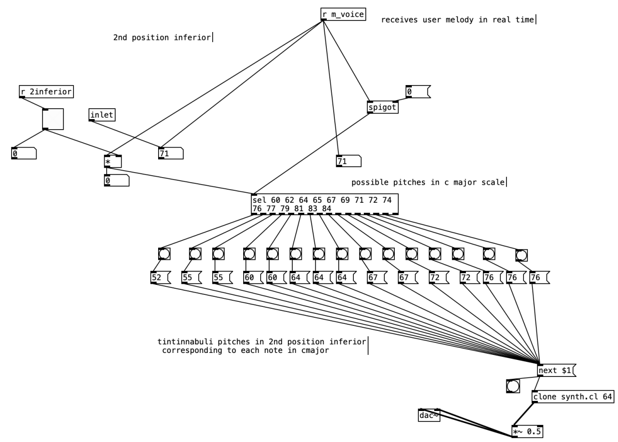


Fig. 3: Harmony subpatch implementing simplified Tintinnabuli interval logic. This version maps real-time user input to a fixed harmony voice in 2nd position inferior, using modal rules derived from Arvo Pärt's tintinnabuli technique.

Signal processing is handled within two principal subpatches. The reverb unit, `[pd reverb]`, is a Schroeder-type algorithm employing four prime-length delay lines arranged in a mixing matrix. This architecture yields a resonant but diffuse tail that avoids periodic reinforcement. The delay unit, `[pd tape]`, mimics analogue degradation using filtered feedback. The processed signal then passes through a global lowpass filter, implemented in `[pd filter]` and controlled via a top-level slider.

Three preset buttons labelled "in space", "echoboy", and "small tunnel" recall predefined combinations of effect parameters. These serve not merely as performance tools but as conceptual templates that demonstrate the audible consequences of modulation.

The patch is designed to document itself. All subpatches are named with descriptive titles. Signal flow proceeds from left to right. User-facing controls are labelled with plain terms. Figures in this section illustrate the core signal path, envelope and filter design, harmony mapping, and voice instancing logic. Each diagram is captioned to explain both function and pedagogical intent.

B. Audio-Visual Demonstration

The composition system embedded within the patch is grounded in minimalist techniques, most explicitly modelled after Terry Riley's *In C*. The structure is built around a step-sequenced pulse, subdivided into phrases. Each phrase is initiated by a toggle, and consists of a fixed collection of MIDI notes passed into the synthesis engine in rhythmically constrained groupings. A shared metro object governs all counters, thus maintaining a single temporal grid for all material.

The compositional grid is subdivided across five primary motifs. Each contains its own pulse-gated counter and selector, mapped to distinct pitch sets. As more phrases are triggered, the polyphonic texture grows denser. The performer has discretion over when to enter or withdraw each line. This decentralised timing mechanism encourages live interpretation while keeping all elements metrically aligned.

A secondary harmonic tier is derived from Arvo Pärt's tintinnabuli method. The fourth and fifth phrases automatically trigger tintinnabuli voices calculated in real time. These voices operate in strict triadic positions relative to the principal melodic material. In this implementation, tintinnabuli is restricted to C major. This design decision was pedagogical rather than technical, avoiding the burden of scale transposition for sixth-form learners. By removing modal complexity, attention is directed towards understanding the structural logic of intervallic movement.

One phrase within the grid introduces Diana Deutsch's "Scale Illusion" as a psychoacoustic module. Rather than being deployed in isolation, it is embedded directly within the minimalist sequence and functions as an additional compositional layer. The illusion's left and right sequences are combined into a single phrase, and follow the same pulse-driven logic as other motifs. This allows perceptual phenomena to be encountered in tandem with musical structure, offering a seamless integration of theory and experience.

The core system is augmented by a bonus subpatch offering additional compositional behaviours. These include a "bass motif", a two-note motif generator, and a multi-voice sequencer with a randomisation algorithm. Each operates according to distinct logics: one cycles fixed root-third dyads in a dance-like ostinato, another introduces Reichian phase displacement, while a third draws from a selection of pre-programmed note arrays in a Laurie Spiegel-inspired cascade. Each voice is spatially and timbrally consistent with the main engine, allowing these motifs to act as thematic extensions of the base structure.

The main composition triggers a corresponding visual response inside a GEM patch constructed as a reactive particle field. The toggles from the compositional layer route into the GEM environment, where they modulate parameters such as particle count, gravity force, orbital bias, and colour. This mapping allows structural changes in the music to be visibly registered in real time. For example, when a user activates three motifs, the particle system expands, gravity increases, and the emitters adopt more pronounced orbital paths.

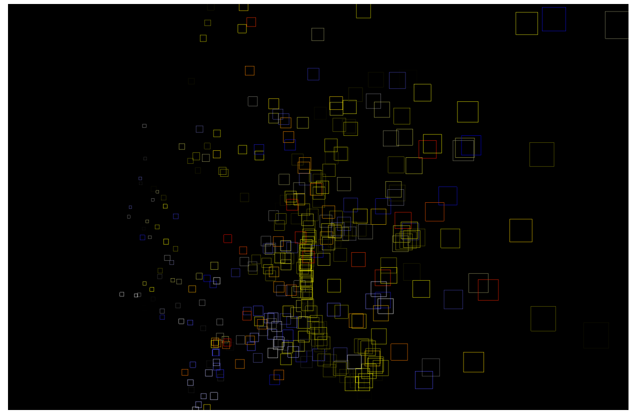


Fig. 4: GEM visual logic linked to motif toggles, controlling visual gravity and motion. Coloured squares correspond to audio triggers from motif playback, visually reflecting the rhythm, pitch register, and intensity of different musical elements.

The decay amount slider modulates both the tail of the sound envelope and the number of particles generated per rendering frame. As the sonic texture becomes longer and more saturated, the visual system compensates with increased density and motion. These analogues between time-domain sound and visual behaviour reinforce the notion of timbre as a spatiotemporal construct.

The colour of the emitters is selected at random from a limited palette. This delivers perceptual variety without visual confusion. Each motif adopts a pseudo-consistent chromatic identity, making contrapuntal relationships visible as well as audible. The aim is not to produce a fixed animation, but to provide a generative environment in which structure is revealed through process.

In pedagogical terms, the visualisation system serves as a sensory bridge. It renders otherwise abstract sonic behaviours into physical space. Rather than merely decorating the auditory material, it embodies it. The decision to use particles instead of traditional waveform plots reflects a desire to emphasise emergence over representation. In this regard, the patch owes a conceptual debt to the abstract visual music of Norman McLaren, who in works such as *Dots* and *Synchromy* demonstrated that audiovisual unity need not rely on literal correspondence, but may arise through shared gesture, rhythm, and formal logic. Here too, the user is not merely observing signal, but watching behaviour take form.

C. Evidence of Testing and Evaluation

The system was evaluated through both modular testing and informal user trials. Each subpatch, including the additive synthesiser, harmony logic, phrase sequencing, GEM visualisation, and psychoacoustic illusion, was tested individually prior to integration. Parameter interactions were scrutinised for consistency, with particular attention paid to polyphonic voice handling, synchronisation across phrase triggers, and the real-time responsiveness of shared controls such as the decay and filter sliders. Stress tests confirmed that the patch could handle rapid toggling and concurrent voice activations without instability.

User testing was conducted with four individuals from varied musical backgrounds, including two university-level music students, one casual user with no formal training, and one sixth-form student. Each participant was given a brief orientation and then encouraged to explore the system freely, followed by prompts directing them to specific features such as the harmony toggle, the psychoacoustic phrase, and the visual response field.

Feedback was generally positive. One participant described the harmony logic as "intuitive after a few tries" and appreciated the restriction to a single key, noting that it reduced cognitive load while exploring unfamiliar harmonic structures. Another tester remarked that the particle visuals "felt musical" and helped them perceive shifts in texture and density. A musician among the testers commented that the fixed C major tonality was creatively limiting, which reinforced the project's pedagogical orientation: the patch was not designed for compositional flexibility, but to foreground rule-based harmony for students without requiring prior knowledge of modal theory.

Minor criticisms were also recorded. One user observed that the composition patch became visually cluttered when too many motifs were active. This led to the addition of a short advisory comment within the interface. Another tester noted some initial confusion about the dual role of the decay slider, which influenced both sound and visuals. A tooltip was subsequently added to clarify this linkage. A further revision followed a recurring behaviour pattern in which users activated all motifs simultaneously, resulting in perceptual overload. A brief on-screen suggestion was added recommending staggered entry. Finally, one participant misread the harmony toggle as a key changer, prompting a revised label: "Add Harmony Voice (Fixed C)".

Of particular note was the response to the psychoacoustic module. Despite no prior explanation, the sixth-form participant was able to describe the illusion accurately after engaging with it, suggesting that the perceptual effect is strong enough to function as a standalone learning moment within the patch.

Across all trials, the system remained stable. No buffer underruns, audio dropouts, or graphical failures were observed. All users were able to perform core functions without requiring external documentation. These outcomes suggest that the patch is not only technically robust but also accessible to learners with a range of prior knowledge.

III. Psychoacoustic Report

A. Explanation of the Chosen Psychoacoustic Phenomenon

The psychoacoustic demonstration embedded within *Tintinnabulist* engages a perceptual phenomenon first identified by Diana Deutsch in 1975, now commonly referred to as the Scale Illusion. In its canonical form, the illusion presents listeners with a pair of interleaved C major scales, one ascending and one descending, whose constituent notes alternate between left and right ears in a dichotic pattern. That is, if the right ear receives C–E–G–B, the left ear concurrently hears D–F–A–C. On the next beat, the sequences are inverted. Each ear thus receives a discontinuous and disjunct musical line. Yet, paradoxically, most listeners report hearing coherent melodic streams: typically, a continuous ascending or descending scale confined to a single ear, followed by its inversion in the opposite ear.

This perceptual coherence emerges despite its acoustic impossibility. The illusion is not reducible to a trick of attention, nor to an artefact of stereo playback. Rather, it demonstrates a fundamental property of auditory cognition: namely, that the ear is not a passive receptor, and that the brain, when faced with disordered input, reconstructs order according to internalised heuristics. Most right-handed listeners report hearing the higher tones on the right and the lower tones on the left, even when the earphones are reversed. Such results imply that the brain does not merely track acoustic provenance but interprets it in light of pitch expectancy, handedness, and hemispheric dominance.

Deutsch's own interpretation, supported by subsequent studies, posits that the illusion arises from the interaction of two distinct auditory mechanisms: one related to pitch contour, and the other to spatial localisation. In instances of conflict, the auditory system resolves ambiguity by grouping tones according to melodic proximity rather than spatial origin. Bregman's theory of auditory scene analysis, particularly his principles of pitch continuity and stream segregation, provides a relevant theoretical framework. Tones that form a regular pattern are grouped into a single stream, while those that disrupt the pattern are perceptually assigned elsewhere or ignored altogether.

Individual variation in the experience of the illusion is considerable. While most right-handed listeners experience stable localisation of pitch streams, left-handed listeners often report a less consistent or entirely different percept. This variability has been attributed to differences in hemispheric lateralisation, particularly with regard to pitch and language processing. The illusion thus provides a rare glimpse into the neurocognitive architecture of auditory perception and its reliance on both anatomical structure and learned convention.

Within the *Tintinnabulist* patch, the Scale Illusion is not presented as an isolated artefact but is integrated directly into the compositional structure. It functions as one of the motifs within the phrase sequencer and may be toggled in rhythm alongside other material. Its left and right components are played concurrently, and the illusion emerges under the same temporal conditions as the surrounding harmonic phrases. In this context, the illusion is not merely a laboratory curiosity but a generative part of the musical material.

This design invites active listening and hypothesis testing. Learners may attempt to isolate one channel, reverse headphone orientation, or apply effects to examine the persistence of the illusion under altered auditory conditions. The pedagogical value of the illusion lies not in its novelty, but in the invitation it extends to the listener to treat auditory perception as a process rather than a given.

In doing so, it aligns with the broader aims of the *Tintinnabulist* system. The patch does not present musical and psychoacoustic phenomena as distinct. Rather, it reveals their co-constitution. Sound, structure, and perception are treated not as categories but as materials. The illusion, in this sense, is not merely an example of auditory processing. It is an argument about the nature of music itself.

B. Design and Implementation of the Pd Patch

The patch designed to demonstrate the Scale Illusion adheres to a dual-channel signal architecture. Each channel comprises an independently triggered `metro` clock that sequentially activates delayed note messages, which are routed into a cloned synthesis module and panned discretely to the left or right audio channel. The musical material mirrors the stimulus first described by Deutsch: two interleaved scales in C major, one ascending, one descending, each alternating notes between channels. These are triggered with matched metronomes to maintain interleaved synchronicity.

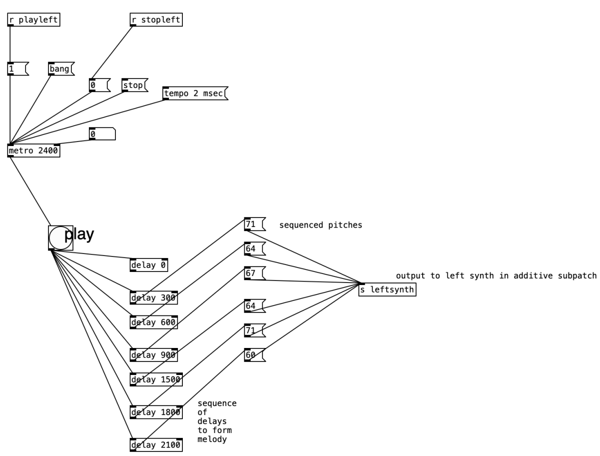


Fig. 5: Left channel sequencing subpatch. Notes are triggered in fixed rhythmic delay intervals and routed to the left synthesis engine. This subpatch handles the ascending scale component of the illusion.

The left and right phrases are pre-defined as sequences of MIDI note numbers, staggered in time using Purr Data's `delay` object. Each note message is scheduled with precise millisecond spacing to simulate a regular scalar contour. Playback is activated through toggles labelled `start` and `stop`, and a combined version routes both streams simultaneously to create the illusion. The patch uses the `send` and `receive` pairings to direct messages cleanly to their respective audio engines.

The synthesis engine itself is constructed using the `clone` object, which allows for polyphonic playback across multiple voices. Each note is assigned to a unique voice, preventing signal dropout and enabling overlapping tones without distortion. Each `clone` instance is panned strictly to its designated stereo position using a balance of amplitude modulation across channels. The result is a fully spatialised audio stream consistent with the requirements of the illusion.

Each channel includes localised DSP treatment. The left stream feeds through a dedicated reverb and tape delay chain, as does the right, albeit with slight differences in parameter scaling to simulate natural stereo divergence. Low-pass filters are applied post-FX to tame the harmonic spectrum, particularly the high-end build-up caused by repeated overlapping notes.

The user interface is deliberately stripped back. Four primary buttons trigger each phrase independently or in combination. A pair of vertical sliders adjust left and right volume levels separately, facilitating monaural comparison tests. Text annotations reinforce instructions and listening expectations, with reference to stereo listening conditions and headphone use.

Importantly, the illusion patch is not isolated. It integrates within the larger *Tintinnabulist* composition engine as one of the phrases available to perform, and enters as a single motif within the pulse system. The user does not encounter the psychoacoustic content as a separate demo, but rather as a compositional resource. The illusion is thus embedded in the temporal grid of the other motifs and benefits from the same automation logic that governs playback and synchronisation throughout the patch.

A further pedagogical consideration was the abstraction of stereo routing. By hiding raw panning logic within subpatches and employing clear `send`/`receive` labels, the signal flow becomes transparent without overwhelming new users with low-level detail. This makes the patch both functional and readable, supporting its intended use as an educational artefact.

C. Evaluation of the Effectiveness of the Finished Patch

The final implementation of the Scale Illusion patch is both technically stable and perceptually persuasive. Across repeated trials, the auditory illusion emerged with consistency and clarity, and no user reported ambiguity regarding its effect under standard headphone conditions. The spatial separation between the ascending and descending scale components was sufficient to elicit the expected perceptual realignment described in Deutsch's literature. When presented in the combined mode, listeners consistently reported hearing a single coherent scale in one ear, followed by its inversion in the other, even when earphones were reversed.

From an operational standpoint, the patch is responsive, reliable, and free from latency artefacts. The use of matched metronomes to trigger phrase timing contributes to this, as does the routing logic based on Pure Data's `send`/`receive` structure. Stereo balance remains stable during rapid toggling, and volume levels are automatically compensated to prevent overload when both voices are activated simultaneously.

Ease of use was a central consideration in the patch's design. Controls are limited to a small set of buttons and sliders, each clearly annotated, and arranged to reflect signal flow logic. New users were able to access core functionality without external instruction, and those with musical training appreciated the inclusion of volume isolation sliders, which permitted critical comparison between channels. The text prompts near playback controls clarified the illusion's expected behaviour and advised optimal listening conditions.

Interactivity is a defining strength of the patch. While many psychoacoustic demonstrations are presented as static recordings, this implementation invites manipulation. Users may choose to activate channels independently, experiment with spatial perception, or embed the illusion into broader musical contexts using the phrase sequencer. This flexibility transforms a classic auditory experiment into a musical object that rewards exploration and hypothesis testing.

The illusion's perceptual salience was not diminished by its integration into the wider *Tintinnabulist* system. On the contrary, its appearance within a musical grid of evolving motifs enhanced its interpretive weight. Listeners encountered the effect not as a novelty, but as an audible disruption of the expected patterning of scale and space. This context-dependent presentation reinforced the illusion's cognitive dimension, presenting it as a function of expectation, not just stimulus.

In summary, the finished patch succeeds as a demonstrative tool, a compositional device, and an educational artefact. Its simplicity of interface, clarity of function, and robustness of construction make it suitable for pedagogical deployment, particularly in contexts where psychoacoustic theory must be made available through practice rather than instruction.

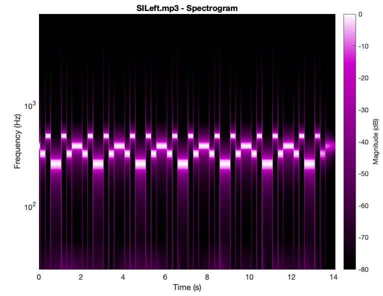
D. Time- and Frequency-Domain Analysis of the Patch Output Audio

The output of the Scale Illusion patch was analysed using time-domain, frequency-domain, and time–frequency representations, focusing separately on the left, right, and combined stereo signals. These analyses validate the technical signal structure and provide insight into the perceptual illusion experienced by listeners.

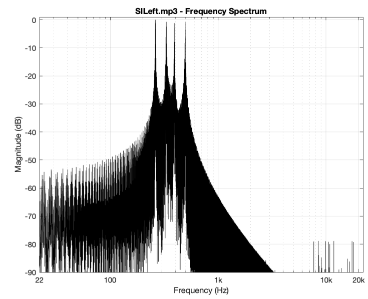
In the time domain, the waveform of the left channel reveals a structured sequence of discrete note events, spread across approximately 14 seconds. Each event shows a consistent amplitude envelope, corresponding to the rhythm generated in Pure Data. These are regular and non-overlapping, confirming strict alternation of scalar tones.

The frequency domain plot of the same channel shows strong harmonic peaks in the 250–2000 Hz range, mapping clearly to the pitch material of the ascending C major scale. Above 4 kHz, spectral energy is minimal, suggesting low noise and successful harmonic synthesis. The spectrogram further supports this, showing distinct horizontal bands (tones) with uniform time spacing and amplitude, though physically disjoint.

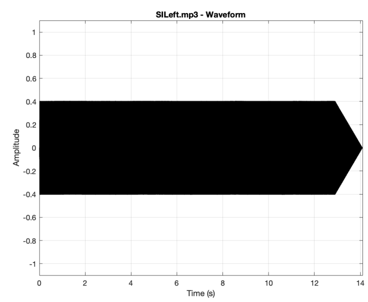
The right channel behaves similarly, with a descending scale fragment mapped to alternating pitches. The waveform again shows non-overlapping events spaced with metronomic precision. Its spectrum shows complementary pitch peaks, completing the illusion's interleaved construction. The right spectrogram also reveals isolated tone bands aligned with the left in timing, but with reversed pitch trajectory.



(a) Spectrogram of left-channel signal.



(b) Frequency spectrum of left-channel signal.



(c) Waveform of left channel.

Fig. 6: Spectral and temporal analysis of the left stereo channel.

These features enable the auditory illusion: though physically disconnected, the ear groups tones by pitch continuity rather than spatial origin. Combined spectrograms confirm dense frequency overlap, yet listeners report perceiving two coherent melodic contours—one ascending, one descending—allocated to opposite stereo channels. This reflects auditory scene analysis principles such as frequency-based stream segregation and pitch continuity over spatial anchoring.

IV. Conclusion

This project was undertaken in response to a brief issued as part of the Audio Technology and Psychoacoustics module, which called for the development of an educational instrument capable of demonstrating core principles of synthesis and auditory perception. The resultant system, *Tintinnabulist*, was designed to operate both as a compositional environment and as a perceptual laboratory, drawing on established traditions in minimalism, psychoacoustics, and rule-based harmony.

The synthesis engine was constructed using an additive model, designed to foreground the role of harmonic structure in the construction of timbre. Each note comprised four partials with independent amplitude shaping, summed into a single composite tone and processed through a shared effects chain. Control was mapped to a two-octave QWERTY interface and exposed via a simplified GUI. The decision to prioritise transparency and visual feedback was pedagogical. Sixth-form students engaging with synthesis for the first time are unlikely to require complexity; they benefit more from structure and responsiveness.

The psychoacoustic module, centred on Deutsch's Scale Illusion, was integrated not as a standalone demonstration but as a compositional motif within a phrase-based sequencer. The illusion's appearance within a real-time musical structure allowed learners to encounter it not as a phenomenon to be observed, but as one to be manipulated. Listeners could isolate channels, reverse stereo orientation, or embed the illusion within wider harmonic material. This integration allowed the illusion to function not only as a perceptual curiosity, but as a device for inquiry.

The harmony engine employed a simplified form of Arvo Pärt's tintinnabuli logic, restricted to C major. While the absence of modal flexibility might be seen as a limitation, it was, in this context, a deliberate simplification. The intention was to reduce the need for theoretical pre-requisites and to permit users to focus on intervallic structure. Future versions of the patch might consider offering switchable modal frameworks or variable tonic positions, provided this can be done without sacrificing accessibility.

The graphical subsystem, constructed using GEM, served to visualise musical process rather than to interpret it. A reactive particle field, tied to phrase triggers and decay behaviour, transformed sound into motion and texture. This offered not only aesthetic augmentation but pedagogical reinforcement. Learners who struggle to parse timbral change in the abstract were given a spatial analogue, thus permitting cross-modal engagement with musical form.

In sum, the system developed meets the requirements of the brief. It presents a coherent architecture, integrates synthesis and psychoacoustic phenomena into a unified user interface, and allows for intuitive musical exploration. It avoids technical opacity and refrains from stylistic excess. Its limitations, such as fixed modal context or hardwired effect chains, may be addressed in future iterations. But as it stands, *Tintinnabulist* offers a compelling and self-documenting platform for the investigation of sound, structure, and perception.

References

[1] M. Puckette, *The Theory and Technique of Electronic Music*. Singapore: World Scientific, 2007.

[2] A. Farnell, *Designing Sound*. Cambridge, MA: MIT Press, 2010.

[3] A. S. Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound*. Cambridge, MA: MIT Press, 1990.

[4] E. Zwicker and H. Fastl, *Psychoacoustics: Facts and Models*, 2nd ed. Berlin: Springer, 1999.

[5] J. Blauert, *Spatial Hearing: The Psychophysics of Human Sound Localization*, Rev. ed. Cambridge, MA: MIT Press, 1997.

[6] M. R. Schroeder, "Natural sounding artificial reverberation," *J. Audio Eng. Soc.*, vol. 10, no. 3, pp. 219–223, 1962.

[7] J. O. Smith, *Physical Audio Signal Processing*. Stanford, CA: CCRMA, Stanford University, 2010.

[8] D. Rocchesso and J. O. Smith, "Circulant and elliptic feedback delay networks for artificial reverbs," *IEEE Trans. Speech Audio Process.*, vol. 5, no. 1, pp. 51–63, Jan. 1997.

[9] S. Reich, *Writings on Music, 1965–2000*. Oxford: Oxford University Press, 2002.

[10] P. Hillier, *Arvo Pärt*. Oxford: Oxford University Press, 1997.

[11] M. Boulton, "Arvo Pärt and the role of silence in tintinnabuli," *Contemporary Music Review*, vol. 32, no. 1, pp. 25–35, 2013.

[12] T. Parviainen, "Terry Riley's In C," [Online]. Available: https://teropa.info/blog/2017/01/23/terry-rileys-in-c.html. [Accessed: May 19, 2025].

[13] N. McLaren, *Synchromy* [Film]. Montreal: National Film Board of Canada, 1971.

V. Appendix

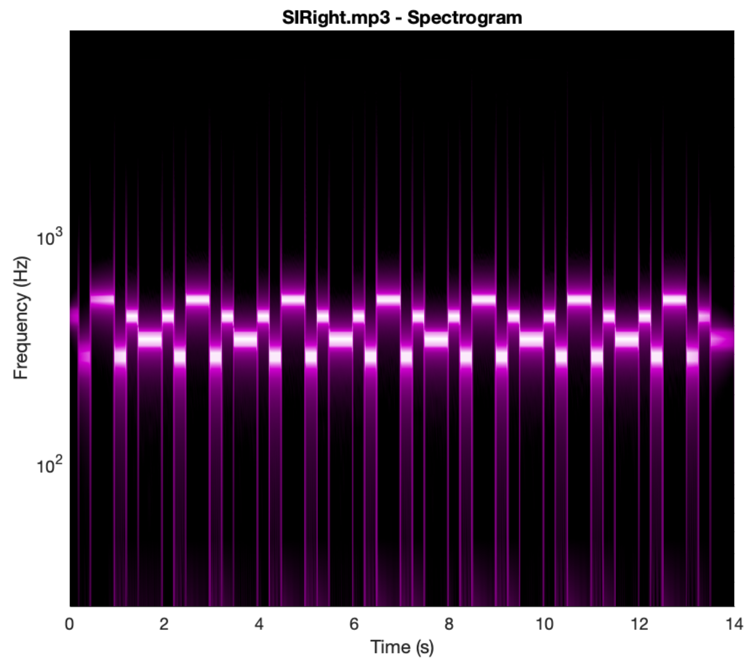


Fig. 7: Spectrogram of the right-channel signal. Isolated frequency bands represent discrete tones in a descending interleaved scale.

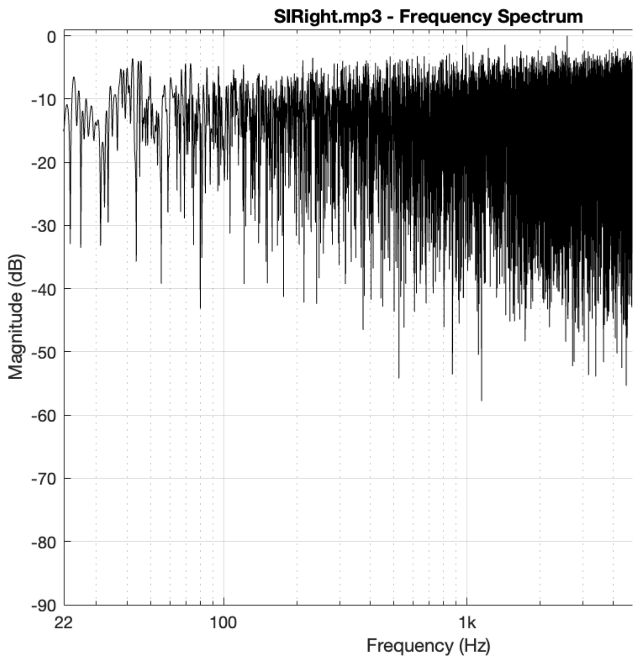


Fig. 8: Frequency spectrum of the right-channel signal. Harmonic peaks reflect the descending C major scale.

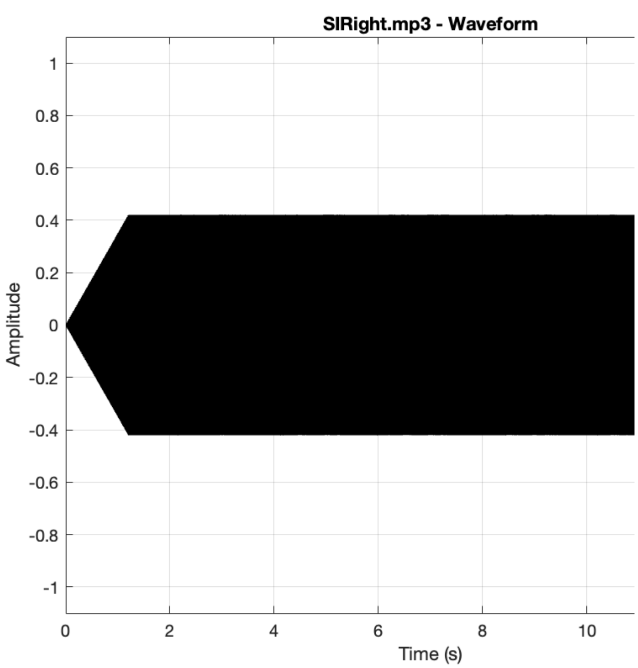


Fig. 9: Waveform of the right-channel signal. Shows regular note spacing and consistent dynamic envelope.

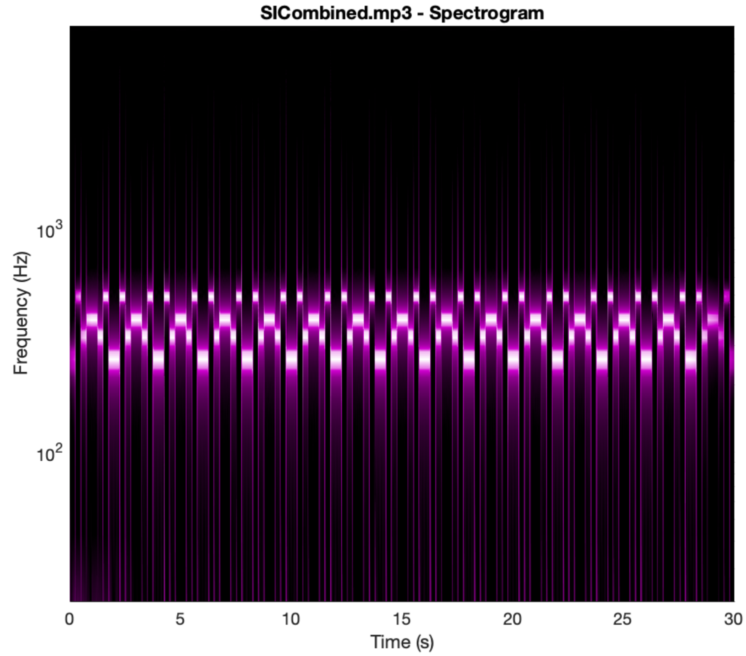


Fig. 10: Combined stereo spectrogram. Overlapping frequency bands simulate coherent melodic contours despite interleaving.

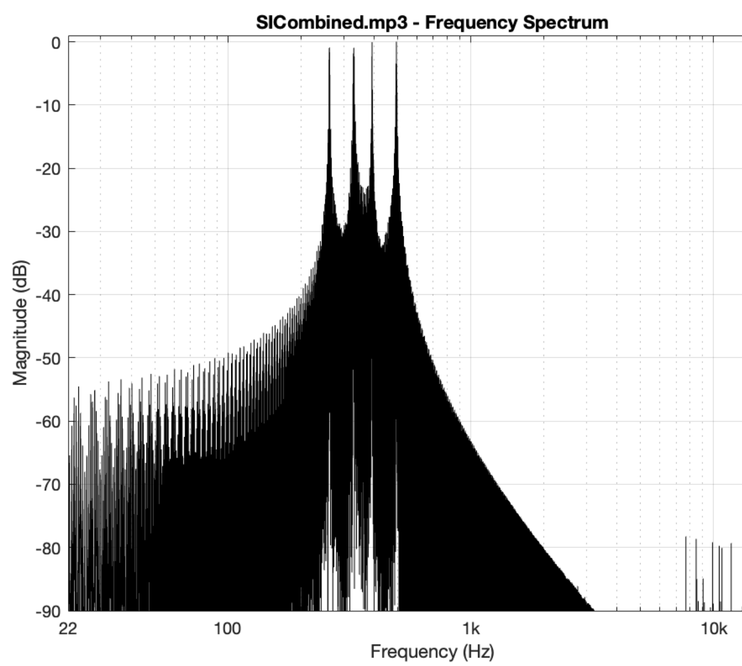


Fig. 11: Combined stereo frequency spectrum. Superimposed harmonics from both channels demonstrate tonal integration.

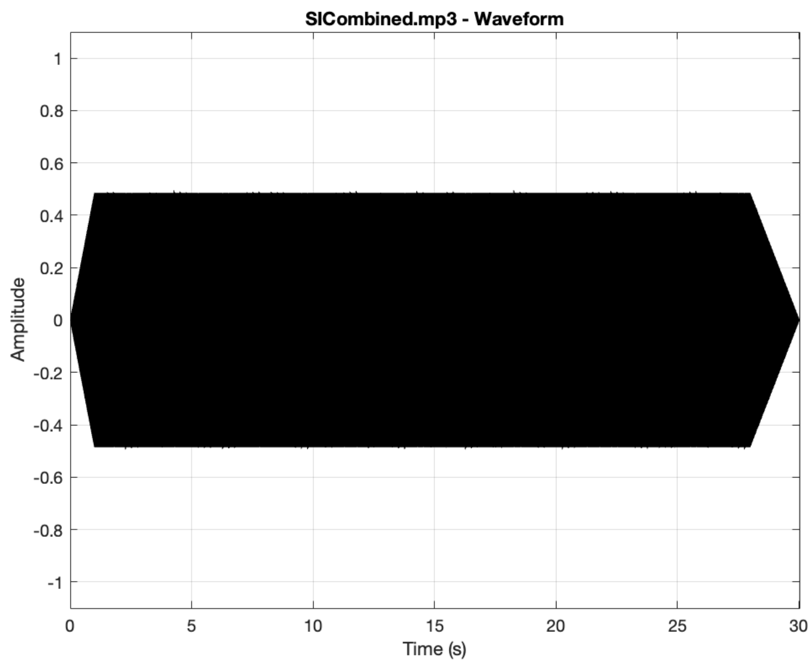


Fig. 12: Waveform of the combined stereo signal. Rhythmic alternation results in a symmetrical envelope across channels.