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Cognitive Inspections of the *Tonnetz*: A Multimodal Approach

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Supported by the CNRS interdisciplinary program, the ProAppMaMu project took advantage of several tools from computational musicology designed to enhance mathematical learning in high schools and universities. One of the main axes of this project focused on cognition, particularly on the ability to detect patterned relationships between geometrical features of pitch spaces and harmonic sequences of chords, and on the impact that these relationships may have on our musical judgements. This paper summarizes two experiments we have conceived for this purpose, paying attention on the *Tonnetz* as a paradigmatic model of neo-Riemannian theories. In a first experiment (completed), participants were asked to identify, among several possibilities, the triangle on the *Tonnetz* matching with the last triad completing a given harmonic sequence; in total, 12 different sequences were provided, as audiovisual coordinated stimuli. In a second experiment (currently ongoing, following a pilot study), participants are being asked to evaluate the inner coherence and stability of 24 harmonic sequences, first presented as pure aural stimuli and secondly matched with their visual counterparts on the *Tonnetz*. We only present here the shared context design of both experiments and their respective aims and methods.

Keywords: music theory, *Tonnetz*, harmonic triads, multimodal interaction

1. Introduction

Neo-Riemannian theories constitute an important subfield of transformational music theory (Cohn, 1998; Lewin, 1987, 1993) applied to tonal music, in which the definition of the harmonic relationships are not subsumed under hierarchical references to the tonic. Instead of emphasizing functional relationships, Neo-Riemannian approaches primarily focus on voice-leading, particularly on parsimonious transformations (Cohn, 1997). Consider any major or minor triad (Figure 1): it can be transformed into three possible chords of the opposite quality while maximizing their pitch-class intersection. In doing so, the voice-leading becomes parsimonious, i.e. the moving voice proceeds by semitone or tone.

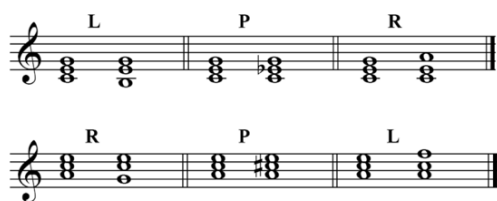


Figure 1. Exhaustive list of the parsimonious transformations (L, P, and R) for major and minor chords.



Figure 2. Equivalent transformations of those in Figure 1 for triads in the [1, 3, 8]-*Tonnetz*.

The LPR family of parsimonious transformations admits a generalization beyond the limits of tonal harmony. Tonal chords are mainly built by superposing major and minor thirds; this principle may apply to further intervallic patterns. Consider for instance the intervals respectively made of 1 and 3 semitones (with 8 semitones completing the octave). With them, it is possible to define two basic qualities of triads and their elemental transformations (Figure 2); they are not necessarily parsimonious, though.

Another very interesting feature of the neo-Riemannian approach lies in its potential to generate pitch spaces. The modern *Tonnetz* representation is a planar lattice of equilateral triangles wherein the three axial directions catch the most favored intervals of triadic tonal music (i.e. the perfect fifth, the minor third, and the major third), the vertices stand for pitch classes, and the triangular cells represent major and minor triads. The intervals of the axial directions can be modified for fitting with non-tonal intervallic patterns as those mentioned above; this particular case leads to the [1, 3, 8]-*Tonnetz*. As a matter of fact, this axial malleability makes mathematically possible to build twelve different *Tonnetze* within the standard modern temperament, i.e. 12-TET system.

Current computational developments made it possible to fully exploit the “metaphor in motion”, which conceptually stands behind transformational music theory (Attas, 2009). This perspective has proven useful for a dynamical coordination of musical sound and visually patterned information on the *Tonnetz* (Cohn, 2012), leading to a much deeper understanding of several structural properties of harmony and voice-leading (Bigo & Andreatta, 2016). Nowadays, several online interactive platforms have been developed (like ours, see Guichaoua et al., 2021) which allow anybody to grasp by themselves the logics behind the *Tonnetz* (Figure 3).

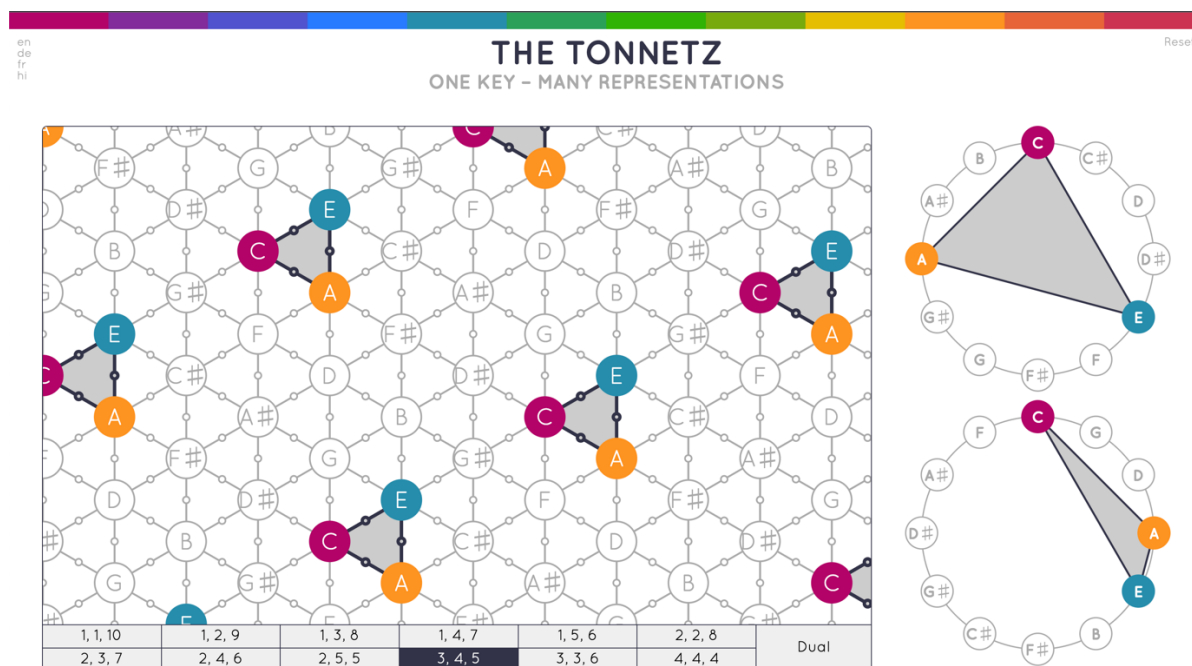


Figure 3. Screenshot of The Tonnetz online platform (<https://imaginary.github.io/web-hexachord/>). The pitch classes of the A minor chord are highlighted.

The development of The Tonnetz online platform was a milestone of the Structural Music Information Research (SMIR) project, carried out at the University of Strasbourg from 2017 to 2019. It was followed by the Processes and Learning Techniques of Mathematical Knowledge (ProAppMaMu) project, from 2020 to 2021, mainly aimed at enhancing mathematical learning by taking advantage of several tools from computational musicology.

One goal of the ProAppMamu project focused on cognition, particularly on the way individuals interact with geometric pitch spaces and neo-Riemannian transformations. The multi-axial structure of the *Tonnetz*, in which intervals unfold in multiple directions, strongly differs from other pitch spaces mainly depending on a vertical image schema for pitches. In addition, the modern *Tonnetz* displays on its vertices pitch classes instead of single pitches, making it more difficult to match them with actual perceived sounds. All that leads to a representation of the harmony which may seem counterintuitive, at least at first glance, for those who are not aware of the geometrical structure behind this particular pitch space.

Previous empirical research has shown a certain consistency between an evaluation of harmonic proximity and the *Tonnetz* structure (Krumhansl & Kessler, 1982; Krumhansl, 1998); more recent computational research has equally found similar consistency (Milne & Holland, 2016). This fact has encouraged neuroscientific hypotheses about the existence of mental key maps behind the perception of music harmony (Zatorre & Krumhansl, 2002); a formulation of such hypotheses is by no means trivial.

Although the conflict between the vertical image schema for pitches and the *Tonnetz* structure was well

highlighted by Candace Brower (2008), no previous empirical research, to our knowledge, has explored the interaction with multimodal platforms for this pitch space. Consequently, two experiments were planned for better understanding, on the one hand, the ability to detect patterned relationships between some geometrical features of the *Tonnetz* and harmonic sequences of chords and, on the other hand, the impact that these relationships may have on our musical judgements. Both experiments required computational adjustments of The Tonnetz online platform, aimed at the purpose.

2. Experiment 1

2.1. Aims

The object of the first experiment, already completed, was to explore the way in which some geometrical features of the *Tonnetz* could be implicitly encoded during an audiovisual interaction with this representational space, as well as to elucidate the cognitive strategies adopted in carrying out this task.

2.2. Participants

88 participants (44.32% female, 55.68% male) took part in the study. They were distributed in 4 different groups (22 people each): music professionals with a solid background in music theory, musicology undergraduate students with some background in music theory, STEM professionals with a solid background in geometry, and STEM undergraduate and master students. The reason for this grouping was to test the impact of the expertise in a twofold way. First, we hypothesized a significant difference between musicians and STEMs with regard to their multimodal performance, by assuming musicians to favor aural

processes and strategies, and STEMs to base their answers on visual aspects. Second, we aimed at further testing the effect of expertise related to each of the two fields. For all participants, previous interaction with the *Tonnetz* and color-blindness were criteria for exclusion.

2.3. Materials

Participants were provided with a digital tablet, a digital pen, and headphones. Stimuli were presented as 12 sequences of 7 block chords each with synthetic organ-like sounds. Chords were major or minor triads in root position; the voice-leading followed the conventional rules of the 4-part harmony. The first 6 chords of each sequence unfolded parsimonious transformations (LR, PR, or PL), lasting 1 second each. The last chord lasted 8 seconds, could also be minor or major, and have 0, 1, or 2 pitch classes in common with the preceding one; the choice of the last chords was planned through the whole set of stimuli, in order to facilitate statistical analysis. The harmonic sequences were synchronized with unfolding trails of lighted triangles on the tablet, according to the geometry of the *Tonnetz* but with no textual cue, unlike The *Tonnetz* online platform. For the 6 first chords of the sequences, triangles matching with major chords were colored in red and triangles matching with minor chords were colored in blue. Simultaneously to the sounding of the last chord, 6 yellow triangles were lighted up. On the *Tonnetz*, these triangles corresponded to variants in terms of quality (whether major or minor) and number of shared pitches with the previous chord; only one of them matched with the sounding chord (Figure 4). In addition to the audio-visual stimuli, materials also encompassed a 3-minute video tutorial summarizing the main features of the *Tonnetz* and a questionnaire. The set of questions was asked to introspect about the experience, and to investigate the cognitive strategies adopted when performing the task.

2.4. Procedure

For each stimulus, participants were asked to choose, among the 6 yellow triangles, the one they thought that visually matched with the last chord they heard. The task was performed twice: first, they performed it without any hint about the structure of the pitch space they had on the screen; second, after watching the video tutorial. In both tasks, the selected triangles and the time spent for making the choice were recorded by the tablet. Finally, participants filled out the questionnaire.

3. Experiment 2

3.1. Aims

The purpose of the second experiment, currently ongoing after unfolding of a pilot study, is to evaluate the influence of the visual representations of harmonic sequences on the *Tonnetz* in terms of coherence (overall harmonic logic and voice leading) and stability (cadential closure of the last chords).

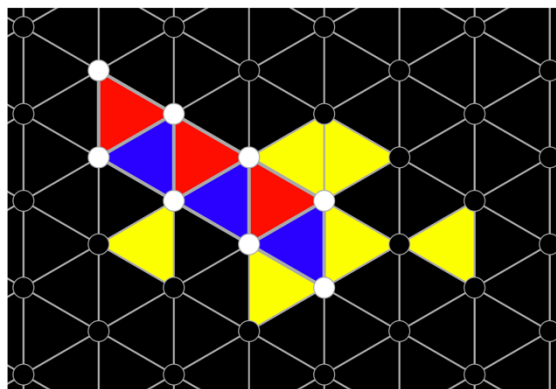


Figure 4. Example of multimodal stimulus for Experiment 1. Top: sequence of chords transcribed with standard notation; bottom: visual representation of the sequence with the six possible answers. For this stimulus, the left-most yellow triangle is the one matching with the final chord.

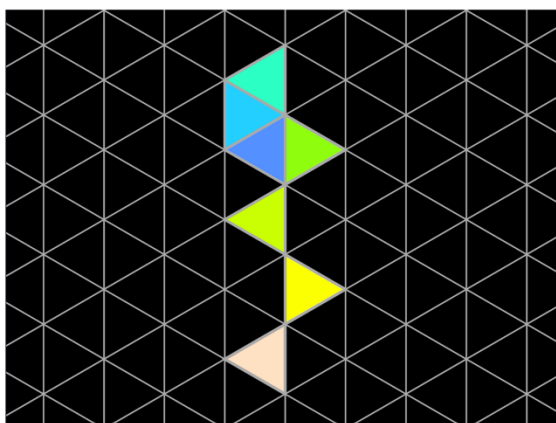


Figure 5. Example of multimodal stimulus for Experiment 2. Top: sequence of chords (tonal and atonal version) transcribed with standard notation; Bottom: visual representation of the harmonic sequence.

3.2. Participants

A pilot version of this experiment has been tested so far by 6 professional musicians. In the final version, there will be at least two groups with different background in terms of musical training. Again, previous interaction with the *Tonnetz* and color-blindness were criteria for exclusion.

3.3. Materials

This time testers were just provided with a laptop and headphones. Stimuli consisted on two sets of 24 sequences of 7 chords, again rendered as organ-like sounds. Chords lasted 1.2 seconds with the exception of the last sustained one. For the first set of sequences (the tonal one), all the chords were major or minor triads in root position; the voice-leading followed the conventional rules of the 4-part harmony. The set was split into 6 subsets according to the following criteria: (1) overall tonal coherence and (2) degree of parsimony. Half of the sequences were tonally coherent with a clear cadential direction. One third of the sequences always followed transformations of the LPR family, another third of the sequences never used parsimonious transformations, and the other third of the sequences mixed parsimonious and non-parsimonious voice-leading. This time, the visual counterpart on the *Tonnetz* was a lighted trail which evolved, in terms of color temperature, from deep blue for the first triangle to beige for the last one (Figure 5). The second set of harmonic sequences emerges from a mapping of the trails of the first set onto the non-tonal [1, 3, 8]-*Tonnetz*. This means that the second set of sequences (the non-tonal one) inherited the structural patterns of the first set of sequences. In addition to these audiovisual stimuli, materials also encompassed two short video tutorials, respectively summarizing some relevant features of the standard *Tonnetz* and of the non-tonal one, as well as four brief questionnaires addressing the reasons for the evaluation of the sequences.

3.4. Procedure

The testers were asked to evaluate the overall coherence of the harmonic sequences and the stability of the cadential closure. First, they evaluated the tonal set of sequences without its visual counterpart. After watching the video tutorial, they were asked to repeat the task, with the addition of the visual representations on the *Tonnetz*. The same task structure was repeated for the non-tonal set of harmonic sequences. The questionnaires were proposed at the end of each block of evaluations.

4. Final remark

As explained above, the first experiment has been already completed (we obtained significant results, currently submitted in a peer-reviewed journal) while the second one is ongoing. Consequently, we have opted for just presenting their respective methods in the proceedings of ICMPC17-APSCOM7. Our aim was to show the adaptability of The *Tonnetz* for diverse experimental protocols. As elucidated in this

presentation, notable differences between the two experiments exist, mainly in terms of the participants' interactivity and their potential grasping of the *Tonnetz* structure. However, both experiments have been conceived for the same purpose: a deeper understanding of the human multimodal interaction with complex pitch spaces, which may lead to improve existing pedagogical strategies within the fields of mathematical and music theory education.

5. Acknowledgements

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