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Space, Sonic Trajectories and the Perception of Cadence in Electroacoustic Music

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Abstract

This paper reports on an exploratory study pertaining to the perception of spatial electroacoustic music. It seeks to understand whether a sensation of "completeness", similar to that associated with the concept of "cadence" in relation to tonal music, can be identified when listening to consecutive sound stimuli distributed around a listener on the horizontal plane. In other words: do particular trajectories feel more "complete" to listeners than others? And what acoustic factors influence this sensation of spatial completeness? In order to investigate this, an experiment was designed that involved asking listeners to evaluate the relative completeness of multiple trajectories, with multiple stimuli, on the horizontal plane. The results show differences in the evaluation of completeness across listeners with differing levels of prior experience with spatial electroacoustic music. They suggest that listeners acquainted with spatial music consider trajectories more complete when presenting the last two impulses at opposite directions from the centre. Listeners who are less acquainted do not show this preference.

Keywords

cadence, spatial perception, sonic trajectory, completeness

Introduction

Spatialisation is central to the practice of electroacoustic and computer music, yet no shared conceptual framework or vocabulary exists for composers to draw from. Kendall and Cabrera (2011, p.1) characterise spatial composition as typically a "tentative and empirical" learning process where "preconceptions about how spatial audio should work" can mislead composers in their investigations. Their work and the work of other authors (e.g. Kendall 1995; Wishart 1996) has sought to translate insights from the spatial hearing and audio engineering literature to electroacoustic music composition in order to provide a practical framework through which to think about spatial organisation. Other writers have drawn on literary and poetic analogues (e.g. Smalley 2007, Palmer 2009), or metaphorical reasoning (Kendall 2010).

This article contributes to practice-led research on spatial electroacoustic music composition by evaluating the applicability of extant music-theoretical concepts to the movement of sound in space, in what we call 'sonic trajectories'. Specifically, the experiment described seeks to understand whether a psychological feeling comparable to the one elicited by "tonal cadence" may be identified within the perception of spatial movement. The organisation of the article is as follows. First, we contextualise our study in relation to work on the perception of cadence, the perception of apparent motion, and the localisation of sound sources. Then, we describe an exploratory study into the perception of "cadence", in which cadence is hypothesised as a perception of change—which may signal opening or closure—within a continuous flow. The results of our study highlight that listeners acquainted with electroacoustic music are capable of discriminating multiple types of spatial configurations and associating them with qualitative judgement on their degree of completeness. A discussion then follows that considers the results in light of music psychology literature on the perception of completeness and acculturation to multi-channel listening.

It is hoped that the investigation presented here may be useful for composers and technologists in developing techniques for the creation of spatial music, and that it spurs further reflection on the appropriation of traditional music theoretical concepts for contemporary practice.

The Perception of Cadence

The concept of cadence has long been of interest to music psychologists. As Caplin (2004) observes, "cadence" identifies a complex concept with multiple perceptual associations that differ historically. Since its introduction into Western music, it has often denoted a specific intervallic formation, and has usually been associated with the ability to provide a feeling of formal closure in response to a harmonic structure called "cadential progression" (Caplin, 2004). Because of this, cadence has traditionally been considered in relation to harmony. However, Lee (1904) has observed that the term finds some correspondence with techniques (e.g. "clausola vera" and "clausola plagalis") that were already used during the middle ages for multivoiced music, before the idea of harmony came to be fully developed. Moreover, the term had a broader meaning than the one in use today. It therefore may be supposed that "cadence" may identify a more general phenomenon, not strictly related to harmonic passages.

Ambiguities in the definition of cadence persist to the present. The term "closure" is often used synonymously with "cadence" in the music theory literature, and sometimes even in combination (see, for example, Sears, 2015). A complete disambiguation is therefore not possible, and research on cadences usually involves experiments investigating multiple types of closure. This problem becomes more complicated as we consider cadence in relation to non-pitched sounds, since clear methods for the evaluation of consonant and dissonant combinations of sounds are not yet available. To avoid ambiguity, in the following sections we decided to restrict our terminology to "cadence" when indicating a field of inquiry; to "closure" when indicating a specific conformation of the stimulus; to "completeness" when considering the perceptual effects of such types of closure on the listener.

Previous studies of the perception of cadence have investigated its relationship to harmony (Sears, Caplin, & McAdams, 2014), melody (Vos & Pasveer, 2002), form (Peebles, 2011), tonality (Cook, 1987), and pitch and timbre (Milne, 2009). A particularly relevant study was conducted by Palmer and Krumhansl (1987). They investigated the correlation between pitch and temporal hierarchies when listening to a piece of music, asking listeners to rate the "degree of completeness" of the excerpts presented in three conditions: pitch condition, temporal condition and combined condition. Results showed that the pitch and temporal conditions did not correlate with each other for listeners unfamiliar with the excerpt, suggesting that listeners were able to identify closures on different musical parameters independently. Similarly, it may be that listeners are able to correctly isolate the closure of a spatial trajectory independently from the harmonic and rhythmic properties of the stimulus.

The perception of completeness seems to be dependent on the previous experience of the listeners and the extent to which they are acquainted with a given musical style. Vos and Pasveer (2002) studied the suitability of melodic intervals for openings and closures across different levels of musical expertise. In one experiment, twelve listeners were asked to evaluate the "degree of completeness" for a variety of two-tone intervals. The results showed that trained listeners rated closures in relation to the consonance of the intervals, while non-musicians had difficulties in discriminating among interval types. In a related study, Sears, Caplin, & McAdams (2014) studied the perception of cadence in Mozart's piano sonatas. They presented short fragments taken from Mozart's repertoire containing authentic, imperfect authentic, half, deceptive and evaded cadences, and asked listeners to rate the degree of completeness of each fragment. They found that traditional cadences play a role in the perception of completeness for tonal music, but non-musicians are unable to discriminate among half cadences, deceptive cadences, and evaded cadences.

The ability to perceive completeness in music is also thought to be correlated to the ability to segment musical phrases into series of hierarchical structures. Peebles (2011) has studied the relation between the ability to segment musical phrases and the perception of completeness, suggesting that listeners are capable of subdividing musical excerpts into smaller units when they are structured using formulaic patterns at specific boundary locations. In a study of excerpts from string quartets by either Mozart or Bartók, Peebles asked listeners to mark endings within each excerpt, as if they were the endings of a paragraph-like section. She did this in order to study the influence of learned musical schemata on the perception of completeness. Her research shows that segmentation remains constant among styles but different mechanisms are used to identify endings (particularly when a musical language is unfamiliar). Furthermore, she showed that experienced musicians feel more confident in detecting musical closures and in assimilating cadential clues from the exposure to unfamiliar genres. Such difference in processing semantic units has also been considered by David Huron (2006, 227), who proposed a distinction between schematic and dynamic expectations. Huron's attempt to explain differences in processing expectations has been formulated in relation to long- and short-term memory respectively. The former notion (*schematic*) would describe the acquisition of semantic units' schemas by repetitive long-term exposure to multiple variations of the same schema in numerous musical pieces, while the latter (*dynamic*) would describe the ability to synthesize and update schemas within a short time frame when exposed to unfamiliar stimuli.

As the above review shows, issues arising from cadence have proven to be a rich field of inquiry for researchers in the cognitive study of music. Yet, while numerous studies have investigated cadence in relation to the perception of harmony, no study of this kind has yet been connected to spatial perception.

Sound Localisation and Broken Motion

A large portion of the scholarship on spatial hearing is dedicated to the study of sound localisation, which refers to a listener's ability to identify the location of a sound event in distance and direction on the horizontal, frontal and median planes. Since the objective of our study is to understand whether listeners are able to qualify spatial relations through the musical concept of cadence, a selective review of our ability to localise sounds in space is necessary, specifically in regard to sound localisation accuracy. The literature on localization blur shows that accuracy in azimuth can range from 2°-3° (front) to about 15° (back) for listeners trained in localising sounds (Carlile, Leong & Hyams, 1997). In three experiments, Recanzone, Makhamra and Guard (1998) studied the localisation accuracy for stimuli with different spectra and found a precision of about 4° for noise stimuli, and 8°-10° for 1-kHz tonal stimuli. Moreover, Klatzky (1998) and Bryant, Tversky and Lanca (2001) have observed a priority in localising objects placed in the front and back over ones placed at the sides.

The basis for our perceptual experiment relies on the assumption that, presented with sequences of impulses that follow different trajectories on the horizontal plane, listeners are able to perceive these trajectories as motion. Understanding the mechanisms involved in the perception of motion for auditory stimuli is an active area of research. Two theories are usually addressed in the literature: the first, called 'snapshot theory', suggests that the perception of auditory motion is an illusion and results from the cognitive comparison of distinct sound "snapshots" at multiple locations, which are then processed through the same mechanisms used for the localisation of auditory sources. For snapshot theory, the first and last locations of a trajectory are enough to permit the perception of movement. The second theory suggests instead that the perception of motion is based on the motion information linking starting and end points (Neuhoff, 2004). For example, direct perception of auditory motion may be able to discriminate motion information like the acceleration or deceleration of diverse sound sources travelling the same distance in the same elapsed time, as in the case of Perrott, Costantino, and Ball (1993). A similar effect is represented by the perception of looming and receding sounds for stationary sonic sources (Schouten et al., 2011), where sounds rising in intensity are often perceived as moving towards the listener, and *vice versa*.

Minimum audible movement angles (MAMA) have also been addressed as parameters to identify either the minimum extent of travel required for the perception of motion, or the minimum distance required for discriminating sounds as coming from different directions (Strybel & Neale, 1994). A paper by Perrot and Pacheco (1989) suggests that the minimum temporal separation between sounds reproduced on different loudspeakers must exceed 100-150ms for best performance in the determination of minimum audible angles (MAA). Strybel and Neale (1994) found that the perception of broken motion for pairs of 50ms noise bursts occurs when the inter-onset-intervals (IOIs) of the noise bursts are between 100 and 400ms; they further observed that the longer the noise burst duration, the greater the IOI threshold for perceived broken motion.

However, this correlation was not linear. For bursts with a duration of 300ms, broken motion was heard reliably for IOIs ranging from 150 to 300ms, even though no silent gap was present. Bremer et al. (1977) presented to their participants trains of impulses displaced as three consecutive clicks occurring in each of three speakers at three locations. They found that the accuracy in the localisation of sources for regularly-spaced trains was higher when the inter-stimulus interval (ISI) between loudspeakers was longer than 200ms, while the same accuracy was achieved for irregularly-spaced trains independently on the ISI. They report that the illusion of movement depends on the IOI, the number of clicks per speaker, and regularity of the pulsing.

Starting from the observation that the movement of sound in space is a central concern in contemporary electroacoustic music composition, we have asked whether a feeling similar to the one of "cadence" may be identifiable for sonic trajectories moving within a circular space. We predicted that, if such a sensation existed, it may vary in relation to the musical expertise of the listener and their acquaintance with spatial electroacoustic music. The next section reports on our study.

The present study

Having observed a lack of scholarship on the perception of cadence outside of tonal harmony, we sought to design an exploratory study that would examine this concept in relation to spatial perception with the aim of developing knowledge that might be useful to electroacoustic composers working with spatial sound. As cadences are usually defined by the relation existing between the last two chords of a musical sentence, we hypothesised that a feeling of completeness may be observable for the last two spatial positions in a sonic trajectory. Specifically, the working hypothesis used for the design of the experiment was based on Danieli (2018). In an attempt to broaden the interpretation of cadence, Danieli suggested that cadence may be understood to involve a perception of change either as a process of closure or of opening. In this way, a feeling of cadence may emerge anytime the listener perceived a strong perceptual change within a continuous flow. A similar approach has been suggested by Lerdahl and Jackendoff (1983, 43), where they subjugate the perception of grouping and phrasing boundaries to the detection of 'pitch jumps' and changes in register, dynamics, articulation, and timbre. As such, we assumed that a feeling of completeness may arise for any sonic trajectory crossing the listener, moving between the two extremes that identify the hypothetical diameter of the ring of loudspeakers in any direction, when considering the listener seated in the centre of the ring. This trajectory is shown in Figure I in the Supplementary Material.

We therefore created stimuli that present the last two impulses at different locations in a horizontal array to study the relatedness between their distance and the feeling of completeness. In accordance with the spatial perception research reviewed above, we also hypothesised that the orientation of the listeners would contribute to the perception of completeness, and that stimuli ending at the front would result in higher ratings, either because of spectral cues related to binaural information or because of the localisation acuity at the front (see Carlile, Leong & Hyams, 1997). The study used different types of stimuli in order to study the phenomenon under various localisation accuracy and broken motion conditions. Since previous research has shown that musical training affects the perception of completeness for different types of closures, this study invited three different groups to participate: composers, performers and amateurs.

We hypothesized that, if a trend in the perception of completeness existed for sonic trajectories moving within a horizontal space, this trend would be accentuated for electroacoustic composers who carry tacit understandings of what works well in the idiom of spatial electroacoustic music.

Method

PARTICIPANTS

In the experiment, 41 participants sat in the centre of a ring of 8 loudspeakers and were asked to rate the level of completeness for sequential stimuli coming from different directions. The participants' ages ranged from 19 to 60 years-old, with mean age of 25.49 and standard deviation of 9.77. Participants were recruited through public advertisement and direct contact, and were paid £10 for an experiment lasting 45 minutes. Ethical approval was granted by the University of Birmingham Ethic Review process. Participants were grouped into three categories:

• amateurs: 18 participants, non-musicians, with no knowledge of the concept of 'cadence'. The knowledge of the concept of 'cadence' was here the discriminatory factor according to which participants were placed within this group, regardless of whether they played an instrument or not;

• instrumental performers (hereafter performers): 12 participants experienced in performing music. Members of this group include performers of Zither and Guzheng, students with grade 8 from the ABRSM in music performance, and musicologists. These participants were familiar with the concept of musical cadence, but had no direct experience of electroacoustic music and the manipulation of spatial parameters;

• electroacoustic music practitioners (hereafter composers): 11 participants, familiar with both the concept of musical cadence and the manipulation of spatial parameters for the composition of acousmatic music works. The group was composed of students undertaking special classes in Studio Composition at the University of Birmingham with at least 1 year of experience in manipulating sounds in space. Professional musicians composing acousmatic music were also included.

STIMULI

For each participant, the experiment included eight tests split into two sets of four. Both sets presented the stimuli shown in Figure 1. The four types of stimuli that were chosen differed considerably in both rhythm and frequency spectrum. The reason for such diversity was that different spectra correlate to different levels of localisation accuracy. For example, the difficulty in locating tonal as compared to white noise stimuli may generate different results; being an exploratory study we wanted to observe the effects of this diversity. Another question during the design of the stimuli was to understand whether closures in pitch and rhythm could impact the perception of completeness of the types of closure involved.

The four types consisted of **a**) a simple non-closure rhythmic pattern, **b**) a rhythmical closure, **c**) an isochronous rhythm, and **d**) a rhythmic and melodic closure. The stimuli were synthesized using SuperCollider (version 3.7.2). Stimuli (**a**) and (**c**) were made up of white noise sounds; (**b**) was created from the synthesis of 40 harmonic sinusoids with fundamental frequency at 2000 Hz; (**d**) was produced from synthesized piano notes playing at frequencies [1920, 2155, 2419, 1812, 1920] Hz, equivalent to a transposition of [C, D, E, B, C].

Three stimuli were composed of 5 rhythmical impulses (**a**, **b** and **d**), and one (**c**) was a dirac comb of 17 equidistant impulses. The stimuli used presented IOIs in line with the research on the perception of broken motion by Strybel and Neale (1994), making the IOI between the last two impulses of all stimuli shorter than 400 ms. The duration of the stimuli patterns varied from 1050 to 2400ms and the impulses within the patterns varied in a range from 100 to 600ms.

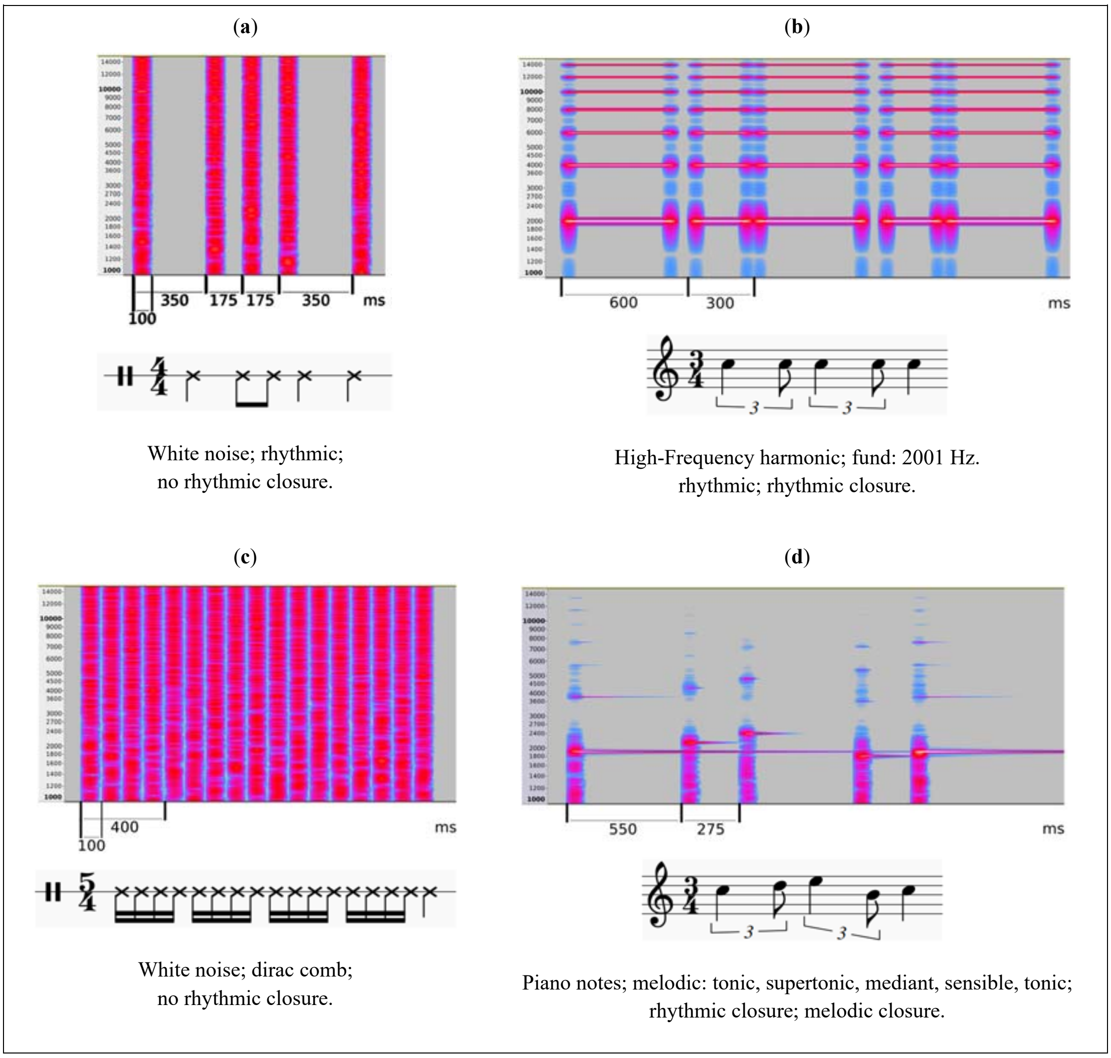

FIGURE 1. Spectrograms of the 4 stimuli and equivalent musical notation.

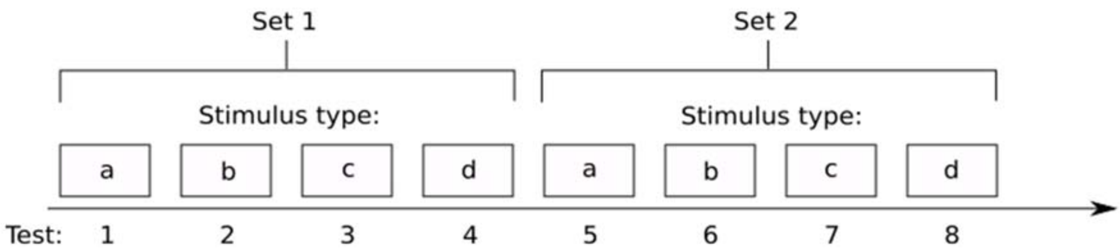

FIGURE 2. Procedure of the experiment.

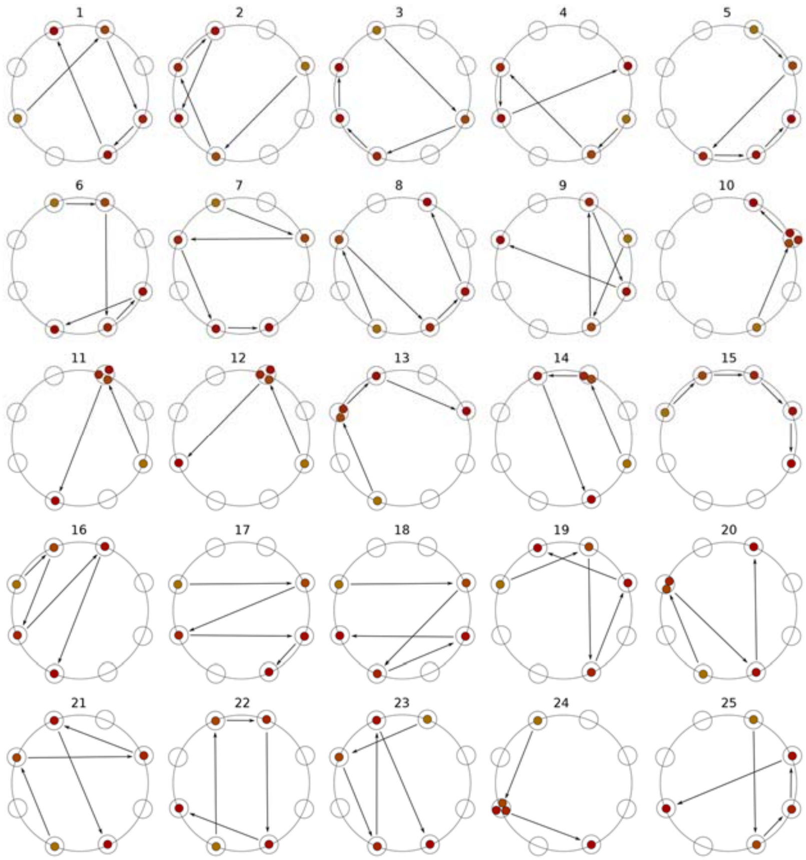

FIGURE 3. Illustration of the 25 trajectories used in the study.

Stimuli (**b**) and (**d**) were designed with longer impulse duration than (**a**) and (**c**) to provide a better support to the listener for the localisation of sound sources. This was due to the assumption that tonal stimuli may negatively impact the accuracy of sound localisation, given that localisation accuracy for tonal stimuli decreases above 1000 Hz (see Recanzone, Makhamra and Guard, 1998).

APPARATUS

The experiment was performed in a low-reverberant studio of the Electroacoustic Music Studios of the University of Birmingham. A map of the room and of the positions of the loudspeakers within the room is provided in Figure III in the Supplementary Material. The vertical and horizontal axes of the ring of 8 loudspeakers were rotated by 22.5°, so to avoid sounds coming from the direct front, back, right and left. Stimuli were run from a desktop Macintosh computer of type Pro, version 6.1. All the 8 loudspeakers used were Genelec 8030A and the audio interface was a Motu, type 16A.

DESIGN AND PROCEDURE

Every experiment presented a set of stimuli in the same order, followed by a repetition of the set. The first set was run to familiarise the listener with the spatial environment. Every participant was asked to partake in both sets in the same order. Each set included 4 tests, and each test presented a different type of stimulus. A schematic representation is given in Figure 2. Every stimulus was reproduced through 5 out of 8 loudspeakers, creating a 5-step trajectory. Only one loudspeaker was playing at a time. Stimuli were heard 25 times in each test, distributed across the loudspeakers via 25 different paths. The same 25 trajectories were presented to each participant, but their order was randomized. Furthermore, the starting point and the direction of each trajectory was randomly determined, to reduce cross-correlations between the sonic trajectories and the listener's orientation. The 25 original trajectories are provided in Figure 3.

The 25 trajectories represent 4 types of closures. These types are characterised by the relation between the last and penultimate positions of the trajectory. For *type 1*, the last and penultimate loudspeakers were adjacent (no. 3, 5, 7, 10, 15, and 17); in *type 2*, they were separated by one loudspeaker (no. 2, 6, 8, 13, 19, 22, and 24); in *type 3*, by two loudspeakers (no. 12, 18, and 20); and in *type 4*, the last two loudspeakers were on the same axis but opposite directions from the centre, i.e. separated by three loudspeakers (no. 1, 4, 9, 11, 14, 16, 21, 23, and 25).

As the amateurs were not aware of the concept of 'cadence', participants were asked to score the level of 'completeness' of each stimulus, on a likert-scale ranging from 1 to 5, within 5 seconds from the end of each stimulus. However, before each experiment, listeners were also provided with the synonyms of 'closure', 'cadence', and 'satisfaction' in order to improve the understanding of the concept.

The variables involved in the study were the group (amateurs, composers, performers), the type of closures (*types 1*, *2*, *3* and *4*), and the final position of the trajectories (1-8), which reflects the orientation of the last impulse in relation to the listener. The experiment thus had a 3x4x8 design. The effect of type of stimulus was not part of the main design, but was investigated post-hoc for composers only (see below).

ANALYSIS

We analysed the results using a linear mixed effects approach, adding variables and interactions incrementally and comparing models through a Chi-square test. The models used for the Chi-square test are reported in Table 2. Random effects included by-subject random intercepts and by-item random intercepts. By-subject random intercepts take account for any variance between subjects in the starting point used in the rating scale (i.e. a difference in baseline rating). By-item random intercepts describe any variance in how participants rate different examples of each trajectory type.

The software environment R was used for the analysis, and the mixed effects model was defined as:

$$\text{model} = \text{lmer}(\text{Rating} \sim 1 + (1|\text{Participant}) + (1|\text{Item}), \text{data}) \qquad (1)$$

A number of custom contrasts were specified, in order to test the hypotheses, which are shown in Table 1. Composers were first compared with both amateurs and performers, and amateurs were compared with performers. One question regarded whether the front-side of the ring of loudspeakers would take a role in the rating of completeness, as characterized by higher frequencies due to head-related transfer function and better localisation accuracy. For this reason, the front was compared with the back, and with the back and sides together. We also compared the left to the right side. As we assumed that a feeling of completeness may emerge in relation to strong perceptual changes, we hypothesized this sensation to be strongest when sonic trajectories moved between the two extremes that identify the hypothetical diameter of the ring of loudspeakers, crossing the listener. As such, we tested closure *type 4* against the other types of closure separately.

Based on the results of this initial analysis, we ran a separate post-hoc pairwise comparison on the group of composers to provide additional material for discussion and better understanding the role of the orientation on the rating of completeness for this group. The model for the analysis was the same as the one used for the entire population, and the three levels for Last Position (front/back, front/back+sides, left/right) were compared for each type of closure.

We also performed a second post-hoc analysis of the effect of stimulus type (**a** – **d**) for the composers only, modelling two two-way interactions; stimulus type by closure type, and stimulus type by last position. The terms were added to the model incrementally and compared using the Chi-square test, as above. The random effects structure was identical to the models described above, with an added random intercept for stimulus set. We specified custom contrasts, predicting stimulus type b to be greater than a and c (because b has a rhythmic closure), stimulus type d to be greater than the rest (because d has rhythmic, tonal and melodic closure), and stimulus type a to be lower than the rest (because it has no closure).

The comparisons from the main analysis were not corrected as these were planned contrasts, but all following post-hoc comparisons were corrected using the Tukey method.

Results

Using our linear mixed effect model, we found significant terms for Last Position (χ^2 (7) = 47.96, $p < .001$), Closure by Expertise interaction (χ^2 (7) = 38.76, $p < .001$), Last Position by Expertise interaction (χ^2 (7) = 62.53, $p < .001$) and Closure by Last Position interaction (χ^2 (7) = 43.1, $p < .01$).

The results show that the perception of completeness depends on three factors: the orientation, the type of closure of the trajectories involved, and the expertise of the listeners. Specifically, our contrast results in Table 3 show that stimuli ending to the right of the participant are perceived as more cadential (see also Figure XI in the Supplementary Material). An interaction with expertise type was also found for stimuli ending in the two loudspeakers directly in front of the listener. Specifically, only composers seemed to judge trajectories ending at the front as more complete.

The results show an interaction between the types of closure and the expertise of the participants: for Composers, *type 4* closures are considered more complete than closures *type 1* ($p<0.001$) and *2* ($p<0.05$, $p\sim0.01$). The Closure by Expertise interaction is reported in Figure 4.

TABLE 1. *Contrasts.*

Variable	Contrast	Identifier
Expertise Type	Composers > Amateurs+Performers	(ET Comp > P+A)
	Performers > Amateurs	(ET Perf > A)
Last Position	Left [0, 5, 6, 7] > Right [1, 2, 3, 4]	(LP Left > R)
	Front [0, 1, 2, 7] > Back [3, 4, 5, 6]	(LP Front > B)
	Direct Front [0, 1] > Back+Sides [2, 3, 4, 5, 6, 7]	(LP DirectF > B+S)
Closure	*Type 4 > Type 3*	(Cl 4>3)
	Type 4 > Type 2	(Cl 4>2)
	Type 4 > Type 1	(Cl 4>1)

Note. Contrasts used for the main analysis of the experiment. In the column 'Variable' are reported the three variables used in the R model. In the column 'Contrasts' are reported the contrasts used to compare the various levels of each variable. The numbers from 0 to 7 represent the positions of the loudspeakers as reported in Figure III in the Supplementary Material. The column 'Identifier' reports the short identifiers used to present the results of the analysis in Table 3.

TABLE 2. *Chi-square test for potential analysis models.*

Name	Model
model 1	Rating ~ ExpertiseType + (1 | Participant) + (1 | Item)
model 2	Rating ~ Closure + ExpertiseType + (1 | Participant) + (1 | Item)
model 3	Rating ~ Closure + ExpertiseType + LastPosition + (1 | Participant) + (1 | Item)
model 4	Rating ~ Closure*ExpertiseType + LastPosition + (1 | Participant) + (1 | Item)
model 5	Rating ~ Closure*ExpertiseType + LastPosition*ExpertiseType + (1 | Participant) + (1 | Item)
model 6	Rating ~ Closure*ExpertiseType + LastPosition*ExpertiseType + Closure*LastPosition + (1 | Participant) + (1 | Item)

Note. The model for the analysis was designed in R.

TABLE 3. *Planned Contrast Coefficients.*

Contrasts	Estimate	SE	d*f*	*p*
Closures				
(Cl 4>3)	-0.0002105	0.04377	2965	0.99616
(Cl 4>2)	-0.02870	0.03171	3787	0.36546
(Cl 4>1)	0.05.878	0.03354	3260	0.07978 .
Expertise Type				
(ET Comp > P+A)	-0.03240	0.1523	38.44	0.83270
(ET Perf > A)	0.1917	0.1601	38.43	0.23853
Last Position				
(LP DirectF > B+S)	0.07102	0.03080	8106	0.02114 *
(LP Front > B)	0.1182	0.02646	8107	< 0.001 ***
(LP Left > R)	-0.1191	0.02661	8113	< 0.001 ***
Closure by Expertise Type				
(Cl 4>3):(ET Comp > P+A)	-0.05.983	0.09025	8100	0.50738
(Cl 4>2):(ET Comp > P+A)	0.1740	0.06805	8100	0.01059 .
(Cl 4>1):(ET Comp > P+A)	0.3901	0.07100	8100	< 0.001 ***
(Cl 4>3):(ET Perf > A)	-0.1317	0.09475	8100	0.16459
(Cl 4>2):(ET Perf > A)	-0.02477	0.07141	8100	0.72869
(Cl 4>1):(ET Perf > A)	-0.09508	0.07484	8100	0.20394
Expertise Type by Last Position				
(ET Comp > P+A):(LP DirectF > B+S)	0.2566	0.06307	8111	< 0.001 ***
(ET Perf > A):(LP DirectF > B+S)	0.02755	0.06490	8112	0.67124
(ET Comp > P+A):(LP Front > B)	0.3749	0.05421	8107	< 0.001 ***
(ET Perf > A):(LP Front > B)	0.03890	0.05704	8112	0.49528
(ET Comp > P+A):(LP Left > R)	0.04695	0.05461	8116	0.38994
(ET Perf > A):(LP Left > R)	-0.01957	0.05707	8110	0.73169
Closure by Last Position				
(Cl 4>3):(LP DirectF > B+S)	-0.2207	0.09557	8106	0.02095 *
(Cl 4>2):(LP DirectF > B+S)	-0.2251	0.06945	8110	0.00119 **
(Cl 4>1):(LP DirectF > B+S)	-0.1592	0.07161	8109	0.02628 *
(Cl 4>3):(LP Front > B)	-0.2313	0.08012	8107	0.00390 **
(Cl 4>2):(LP Front > B)	-0.09311	0.06006	8109	0.12112
(Cl 4>1):(LP Front > B)	-0.1461	0.06291	8109	0.02024 *
(Cl 4>3):(LP Left > R)	-0.1005	0.08013	8106	0.20999
(Cl 4>2):(LP Left > R)	0.09584	0.06016	8108	0.11118
(Cl 4>1):(LP Left > R)	0.01563	0.06297	8109	0.80395

Note. Between-groups linear mixed effect analysis; Cl means ‘Closure Type’, ET means ‘Expertise Type’, LP means ‘Last Position’; ‘Comp’ means ‘Composers’, ‘P+A’ means ‘The groups of performers and amateurs’; ‘Perf’ means ‘Performers’, ‘A’ means Amateurs; ‘DirectF’ identifies the two loudspeakers directly in front of the listener, ‘B+S’ identifies of the ratings at the back and sides, ‘B’ means ‘Back’, ‘R’ means ‘Right’; . identifies $p<0.1$, * identifies $p<0.05$, ** identifies $p<0.01$, *** identifies $p<0.001$.

TABLE 4. *Within-group analysis of LastPosition for Composers.*

Contrasts	*Estimate*	*SE*	*df*	*p*
Closure = 1				
LP Front > B	*0.41265085*	*0.09566770*	*2133.84*	*0.0002 ****
LP DirectF > B+S	*0.14166911*	*0.10925531*	*2157.56*	*0.9058*
LP Left > R	*-0.16967977*	*0.09536882*	*2158.18*	*0.5783*
Closure = 2				
LP Front > B	*0.40648000*	*0.08937969*	*2156.92*	*0.0001 ****
LP DirectF > B+S	*0.53635178*	*0.10157981*	*2155.38*	*<.0001 ****
LP Left > R	*-0.16601666*	*0.08965073*	*2156.23*	*0.5196*
Closure = 3				
LP Front > B	*0.50911836*	*0.13869922*	*2153.99*	*0.0029 ***
LP DirectF > B+S	*0.37210772*	*0.16451318*	*2157.08*	*0.2372*
LP Left > R	*0.12393624*	*0.13903359*	*2157.92*	*0.9940*
Closure = 4				
LP Front > B	*0.16887156*	*0.07865982*	*2158.93*	*0.3043*
LP DirectF > B+S	*-0.05654927*	*0.09554841*	*2151.87*	*0.9999*
LP Left > R	*-0.10986395*	*0.07914828*	*2100.64*	*0.8606*

Note. Linear mixed effect analysis for the group of composers; for each type of closure, multiple directions have been contrasted. ‘LP Front > B’ analyses the size of the effect obtained for the four loudspeakers in the front [0,1,2,7] against the ones behind the listener [3,4,5,6]. ‘LP DirectF > B+S’ analyses the two loudspeakers directly in front of the listener [0,1] against the ones placed at the sides and behind the listener [2,3,4,5,6,7]; ‘LP Left > R’ analyses the difference between stimuli ending in the left and right halves of the ring of loudspeaker; * identifies p<0.05, ** identifies p<0.01, *** identifies p<0.001.

TABLE 5. *Chi-square test for the post-hoc analysis of the effect of stimulus type for composers only.*

Name	Model
model 1	Rating ~ (1 | Participant) + (1 | Item) + (1|Set)
model 2	Rating ~ Closure + (1 | Participant) + (1 | Item) + (1|Set)
model 3	Rating ~ Closure + LastPosition + (1 | Participant) + (1 | Item) + (1|Set)
model 4	Rating ~ Closure + LastPosition + StimulusType + (1 | Participant) + (1 | Item) + (1|Set)
model 5	Rating ~ SimulusType*Closure + LastPosition + (1 | Participant) + (1 | Item) + (1|Set)
model 6	Rating ~ StimulusType*Closure + StimulusType*LastPosition + (1 | Participant) + (1 | Item) + (1|Set)

Name	Npar	AIC	BIC	logkik	deviance	Chisq	Df	Pr(>Chisq)
model 1	5	6761.8	6790.3	-3375.9	6751.8			
model 2	8	6736.6	6782.1	-3360.3	6720.6	31.241	3	<.0001 ***
model 3	15	6686.0	6771.4	-3328.0	6656.0	64.579	7	<.0001 ***
model 4	18	6662.3	6764.8	-3313.1	6626.3	29.698	3	<.0001 ***
model 5	27	6667.5	6821.3	-3306.8	6613.5	12.792	9	0.1723
model 6	48	6693.5	6967.0	-3298.8	6597.5	15.968	21	0.7714

Note. The model for the analysis was designed in R.

TABLE 6. *Post-hoc analysis of the effect of stimulus type for composers only.*

Contrasts	*Estimate*	*SE*	*df*	*p*
b > a + c	*0.02608*	*0.05679*	*2167.26305*	*0.64609*
d > a + b + c	*0.24157*	*0.05350*	*2167.23501*	*<.001 ****
a < b + c + d	*0.22398*	*0.05356*	*2167.25072*	*<.001 ****

Note. Linear mixed effect analysis for the group of composers; for each type of stimulus, multiple directions have been contrasted. 'b > a + c' analyses the size of the effect obtained for stimulus type **b** against types **a + c**. 'd > a + b + c' analyses size of the effect obtained for stimulus type **d** against the other stimulus types; 'a < b + c + d' analyses the size of the effect obtained for stimulus type **a** against the other stimulus types; *** identifies p<0.001.

The type of closure is also affected by the position of the last impulse of the stimulus (see Table 3). Specifically, the difference between Closures *type 4* and the other types of closures changes in relation to the stimuli's last position. The increased ratings for last position in the front were not as high for Closure *type 4* as for the other Closure types. These results suggest that *type 4* closures are less affected by the orientation of the listener than the other types of closures (see Figure 5). Plots depicting the Closure by Last Position interaction are available in the Supplementary Material section (see Figures III, IV, and V).

The post-hoc analysis of effects of closure type and last position for composers only is reported in Table 4. We found an increase in ratings for Closure *types 1* (p<0.001), *2* (p<0.001) and *3* (p<0.01) but not *4* (not significant) when terminating in the half front of the ring (loudspeakers [0,1,2,7]). An increase in ratings has also been observed for Closure *type 2* when comparing the two loudspeakers placed directly in front of the listener [0,1] against the remaining loudspeakers in the ring.

In the second post-hoc analysis focusing on the effect of stimulus type on ratings among the composers, we found a significant main effect of stimulus type and no interactions (Table 5). There were also main effects of closure type and last position, consistent with our primary analyses reported above. The contrasts between stimulus types is presented in Table 6. These showed that stimulus type d, which included a sequence with rhythmic, tonal and melodic closure, was perceived as having more closure than the other sequences. Stimulus type a was perceived as having less closure than the other sequences, likely due to its lack of structural closure. There was no significant difference between stimulus type b versus a and c, despite it having rhythmic closure.

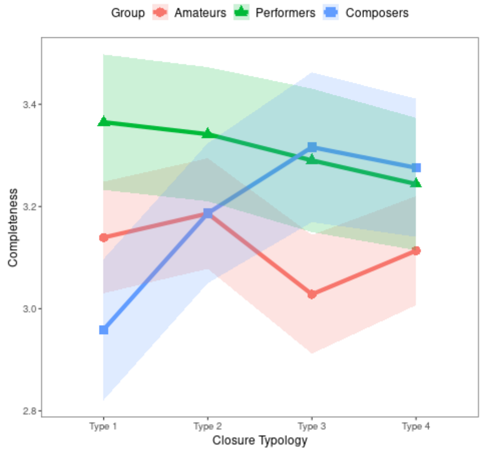

FIGURE 4. Interaction between groups and closure typology.

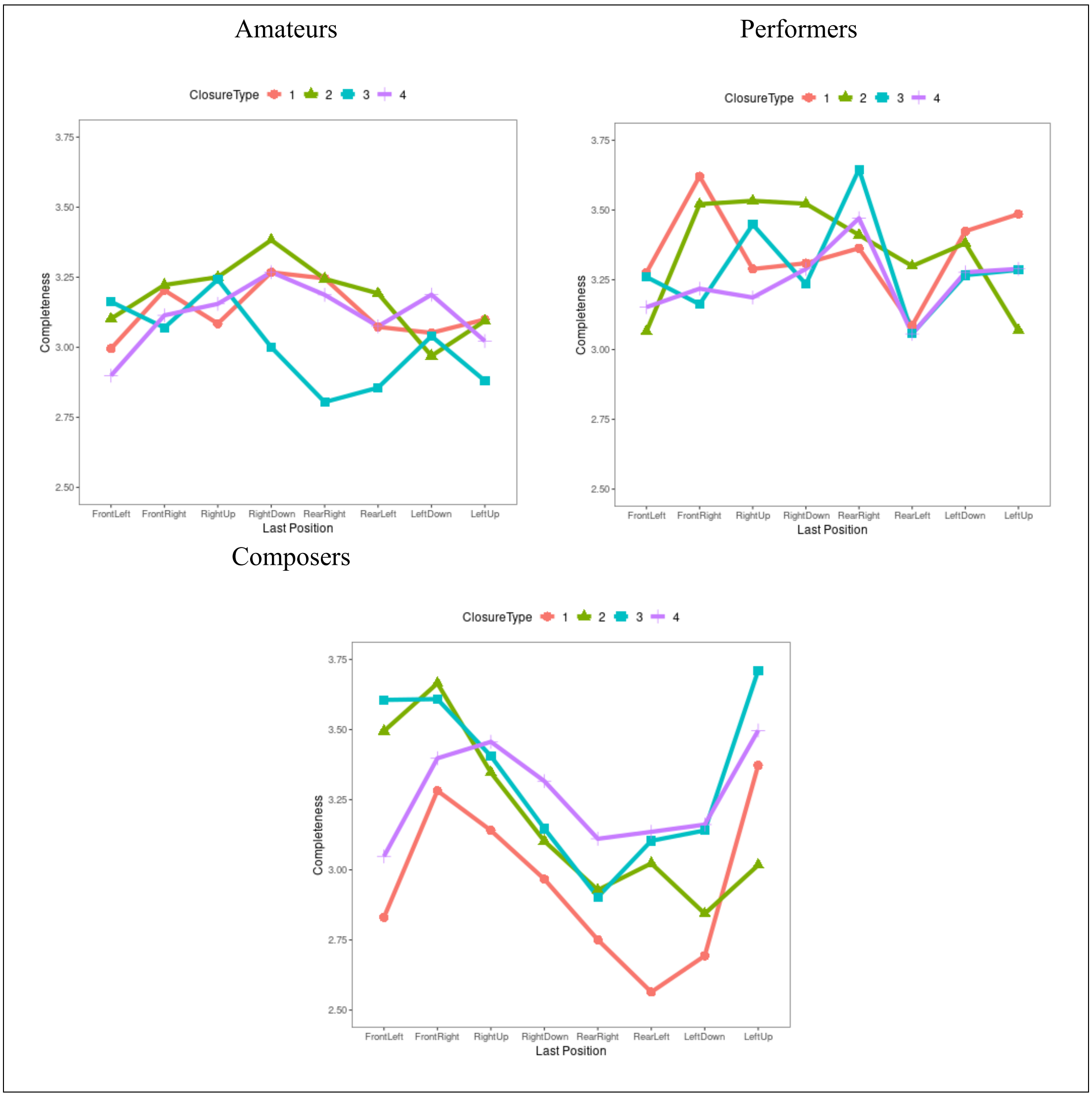

FIGURE 5: Interaction between closure typology and the position of the last impulse of the stimuli for each group – top-left: amateurs; top-right: performers; bottom: composers.

Discussion

The experiment identified a role of closure in the rating of completeness of sonic spatial trajectories and a difference between composers and the rest of the participants. Since we noticed an effect of spatial closure across multiple types of stimuli, it may be that listeners acquainted with spatial listening can isolate spatial motion as an independent musical parameter. Similarly to the findings of Palmer and Krumhansl (1987) which show listeners process pitch and temporal closures independently and hierarchically, space might also contain syntactic elements that contribute to the understanding of the musical syntax. This may, however, only be true for listeners acquainted with spatial music, suggesting that musical expertise may affect the identification of closures. This assumption is similar to the results from Sears, Caplin, & McAdams (2014), who highlighted differences in the perception of harmonic cadence between musicians and non-musicians. In this case, acquaintance with spatial listening may improve the perception of cadence in relation to sonic motion.

As it is visible in Figure 4, composers tended to consider closure *type 4* as more complete than *types 1* and *2*. This difference in closure perception can be seen more clearly between closure type 1 and 4 in Figure 5. Figure 5 also shows that closure *type 1* is rated lower than the other types of closure for the group of composers except for when ending at the left-up location.

Closures *type 4* were less affected by the orientation of the listener than the other types of closures overall. Closures *type 1*, *2* and *3* (Table 3) presented, conversely, a higher increase in the rating of stimuli ending in the front compared to *type 4* at a population level. A similar pattern of results was found in the within-group analysis for the group of composers (Table 4), in which the results suggest that closures *type 4* were less affected by the orientation of the listener. For the other types of closure, when rating the level of completeness of one trajectory, listeners seem to prefer those ending in the front half of the ring. Specifically, closure *type 2* seems to be more dependent on orientation than the other types of closure, presenting an increase in ratings when trajectories end in the two loudspeakers placed directly in front of the listener. We also observed that closure *type 3* produced a moderate effect size for the same orientation, although its p-value was not particularly low, which means there is a greater probability that the effect was observed by chance. An explanation for this may be that closures *type 1* and *4* are easier to identify, so listeners could rate them consistently. When closures lie between these two extremes – as is the case with *types 2* and *3* – closures may appear more ambiguous, and the listeners may rely more on perceptual factors like spectral cues. This may help explain the interaction effect between closure type and last position observed in this study, as the loudspeakers in the direct front may be characterised by brighter spectra due to the Head-Related Transfer Function (HRTF) of the listeners, which may become a factor of preference in ambiguous circumstances.

Cultural exposure to multichannel listening seems to take an important role, and facilitates the identification of completeness for different types of closures. Similarly to the studies by Sears, Caplin, & McAdams (2014) and Peebles (2011), who report that both the discernment of cadence types and the segmentation of musical sentences depend on the expertise of the listener and exposure to the musical style presented during the test, the role of closure in the perception of completeness seems to depend on familiarity with electroacoustic music. Figure VI (Supplementary Material) may suggest that some training effect may take place.

One question is whether the concept of ‘cadence’ is the right one to represent the phenomenon observed: namely, the varying perceptions of completeness for particular spatial trajectories.

Different alternatives could be considered to explain the phenomenon. The ratings could be seen as a reflection of spectral differences in the loudspeakers. In this case, the phenomenon would be an outcome of a change in the clarity of the sound or a symptom of localisation accuracy, which supposes the sound to pass from less certain (the back) to more certain locations (the front). However, this objection is weakened by the fact that the group of composers has rated cadences of *type 4* as more complete than those of *type 1* regardless of the orientation of the last impulse. Spectral differences may become more important for closures that lie between *type 4* and *type 1*. However, the results obtained in Table 3 found that the orientation of the last impulse has an effect on the whole population. This may suggest that listeners who are not familiar with spatial listening may be more inclined to rely on spectral cues.

Differences in ratings among stimuli may also be consequent to differences in the perception of the stimuli's structures. Although the IOIs for the last two impulses were always < 400ms, stimulus types **b** and **d** presented intervals of 600 and 550ms respectively between the third and fourth impulses of each stimulus. This raises questions about whether those stimuli were perceived as whole trajectories or were perceptually split into pairs of stimuli, and therefore whether the perception of the trajectory was a perceptual or a cognitive phenomenon. If the phenomenon was perceptual, it may imply that the sequential presentation of the last two impulses would have a direct impact on the listener's cognitive process of motion, and therefore the perception of completeness may be connected to the perception of movement. On the other hand, if the ratings were a cognitive abstraction of the trajectory paths, the rating would be based less on motion perception and more on the abstracted representation of a spatial map. This may be considered in relation to the results obtained in this study, implying the possibility for composers to be more flexible and responsive than the rest of the population when abstracting trajectory paths due to their previous experience with this mode of listening. However, it is not possible to answer this question at this stage, as our analysis has shown no interaction among Closure and Stimulus type, so that the type of stimulus does not directly affect closure perception. On the contrary, this analysis suggests that the perception of closure for spatial trajectories may be independent from the type of stimulus involved, and potentially be a stand-alone phenomenon. More research is needed in this direction to understand what range of parameters may elicit such a phenomenon.

Future improvement

As an exploratory study, a greater number of variables were included than would be the case for a more systematic experiment. Different stimulus types were used to rule out the possibility that listeners' evaluations of completeness were influenced by invariable acoustic factors that might influence the stimulus in a predictable way (for instance, nodes and antinodes caused by room modes, or spectral differences in the loudspeakers). Our approach consisted in providing the listener with multiple spectra, so as to uncouple the stimulus from invariable acoustic implications. Further research might exert more direct control over the stimuli or the room, for example by conducting the experiment in a room with variable acoustics. Since the experiment made use of non-transitional point-source stimuli, using continuous sounds that transition between loudspeakers may produce different results. Further studies may also be conducted to investigate what behaviours can be observed through the use of phantom sources and stereo-projection.

Conclusions

This study identified a new set of questions for research in spatial electroacoustic music, one that has the potential to impact music theory, electroacoustic composition, and hearing science. Furthermore, the study points to a new direction in electroacoustic music research, where concepts that have their roots in traditional music theory (in this case, in music of the common practice period) may be re-appropriated for contemporary practice.

Composers often lament the lack of non-technical theoretical resources pertinent to the process of composing in the electroacoustic medium. By demonstrating an effect of sonic trajectories on the feeling of completeness, our results go some way to filling this gap. Of particular relevance to this question is the finding that composers demonstrate agreement. The results suggest that there may exist a correlation between the feeling of completeness and the types of closure involved. Studying experiences of completeness in the electroacoustic medium therefore seems to be a fertile area of research.

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