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Tracking auditory attention in group performances: A case study on Éliane Radigue's *Occam Delta XV*

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Authors contributions. C.C. and E.M.-B. designed the experiment. C.C., E.M.-B., and A.G. collected the data. C.C. prepared the analysis plan and A.G. pre-processed and analyzed the data. C.C. and E.M.-B. wrote the paper.

Abstract

While the empirical study of the processes and mechanisms underlying joint musical performance has gained a lot of traction in the past few decades, surprisingly little attention has been paid to the study of musicians' listening strategies in what remains a mainly audio-centric medium. Yet, understanding how musicians listen to each other is particularly crucial for more open-ended, improvised, or indeterminate musical practices, as it plays a crucial role in shaping how the performance will unfold. In this paper, we report on an exploratory study that was designed to investigate the dynamics of musicians' auditory attention in such settings, using Quatuor Bozzini's performance of Éliane Radigue's *Occam Delta XV* (2018) as a case study. Using a post-hoc annotation procedure, we found striking differences between musicians' overall auditory attention, with each musician's listening orientation relating differently to the general narrative of *Occam Delta XV*. We also found that joint listening between musicians was more likely to emerge when coordination was more challenging, suggesting that attentional focus was used strategically by the performers as a way of enhancing coordination within the group. Taken together, our findings shed important light on musicians' listening and interactional strategies in collective music-making.

Keywords: listening; attention; collective performance; indeterminate music; improvisation.

Figures

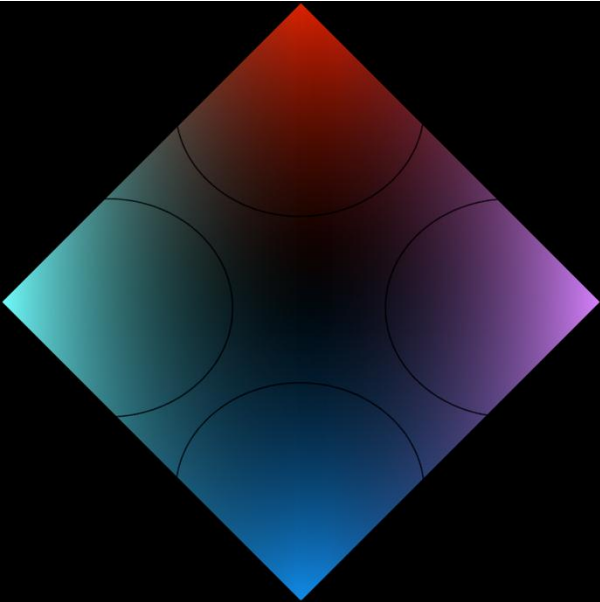


Figure 1. Digital interface used by the participants to record their attentional focus during the performance.

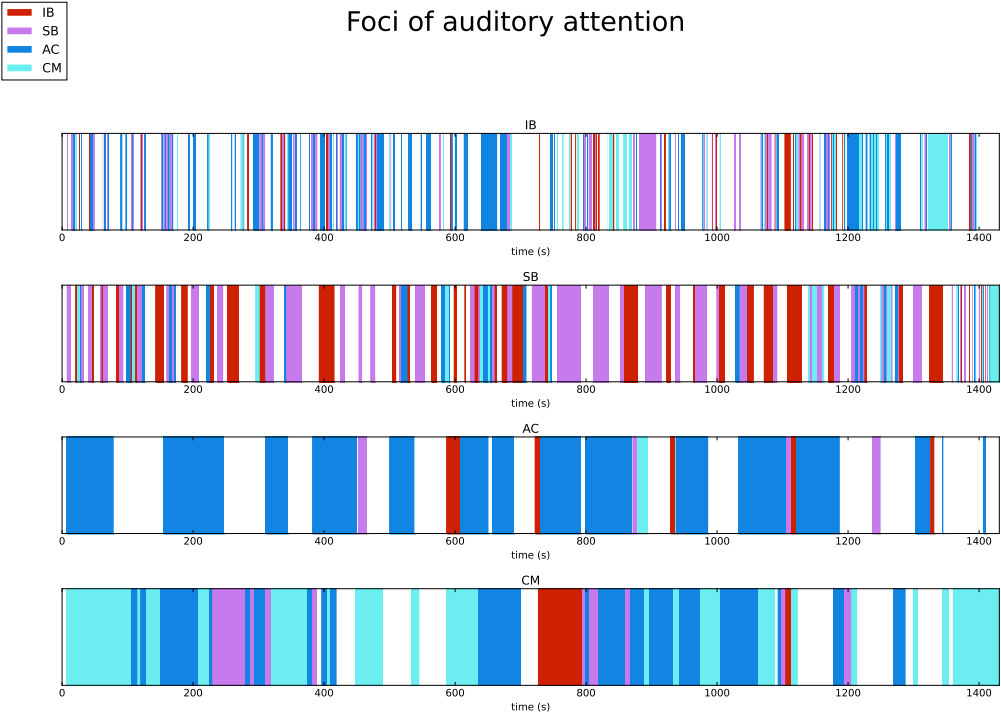


Figure 2. Focus of auditory attention for each musician at each moment of the performance. White indicates the musician's report that they were listening to the overall sound of the quartet.

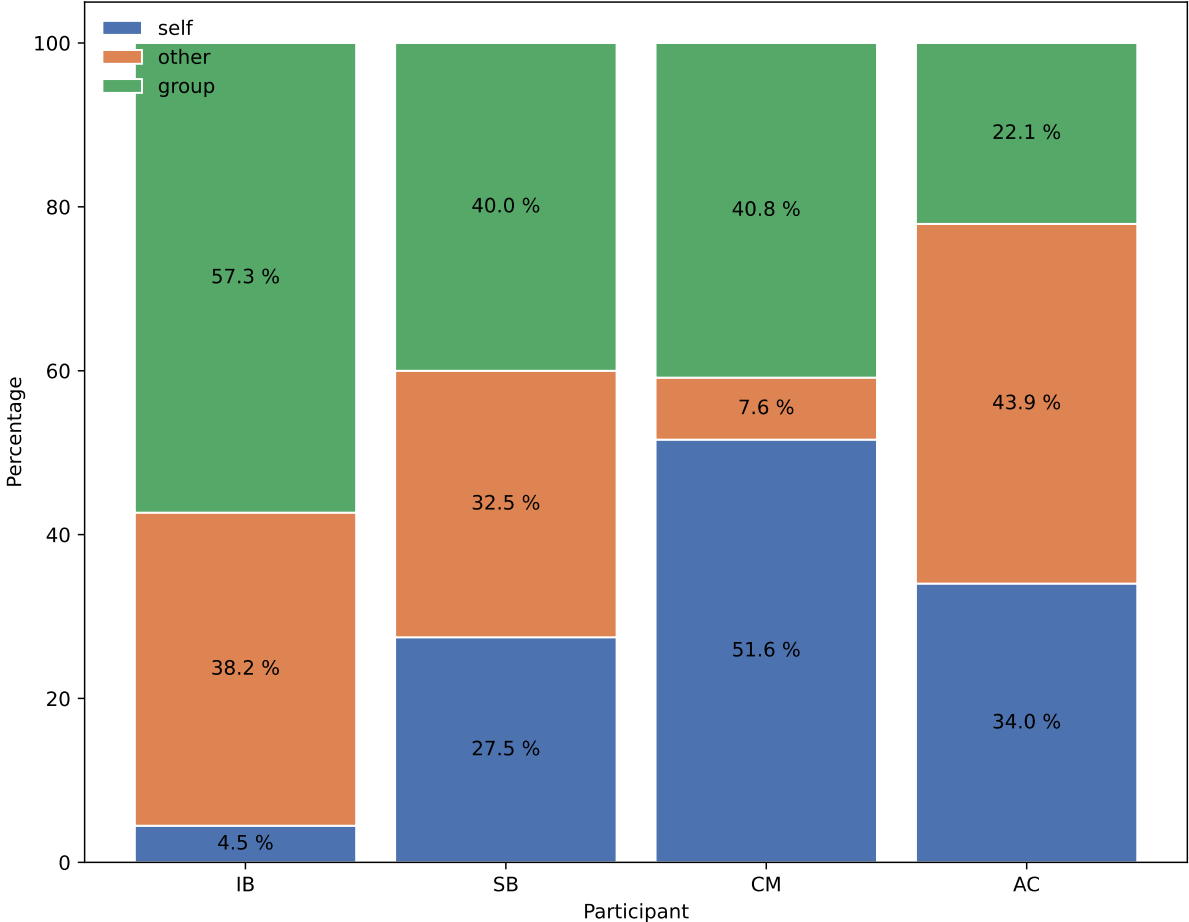
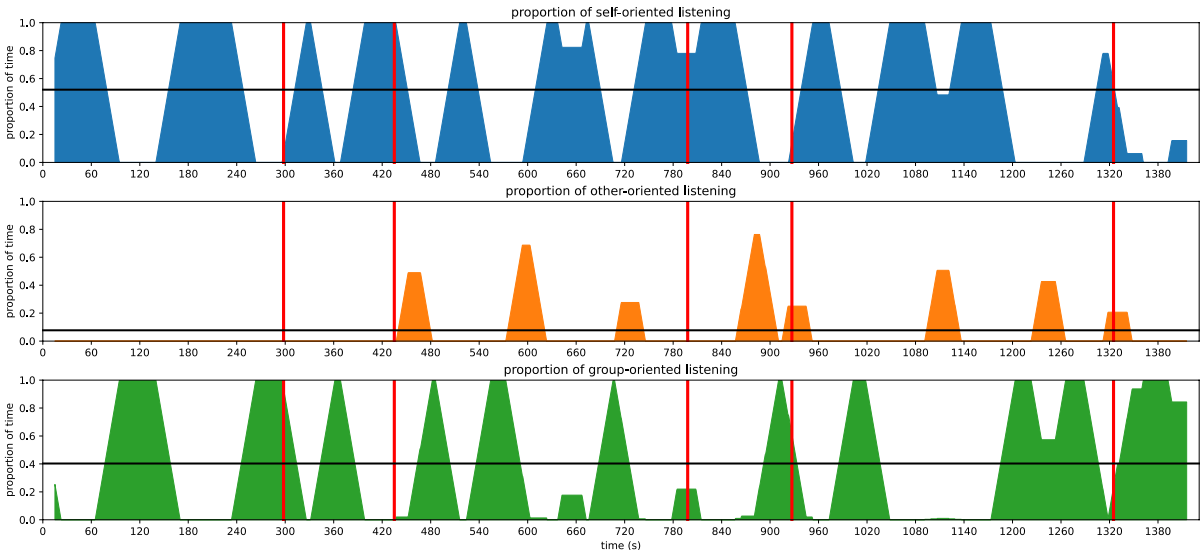
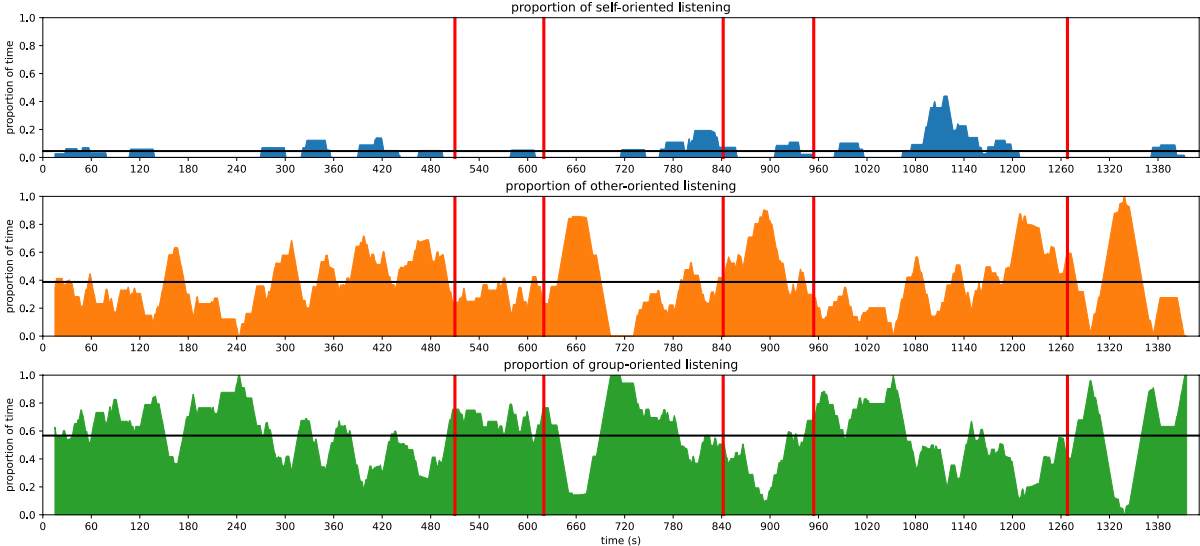


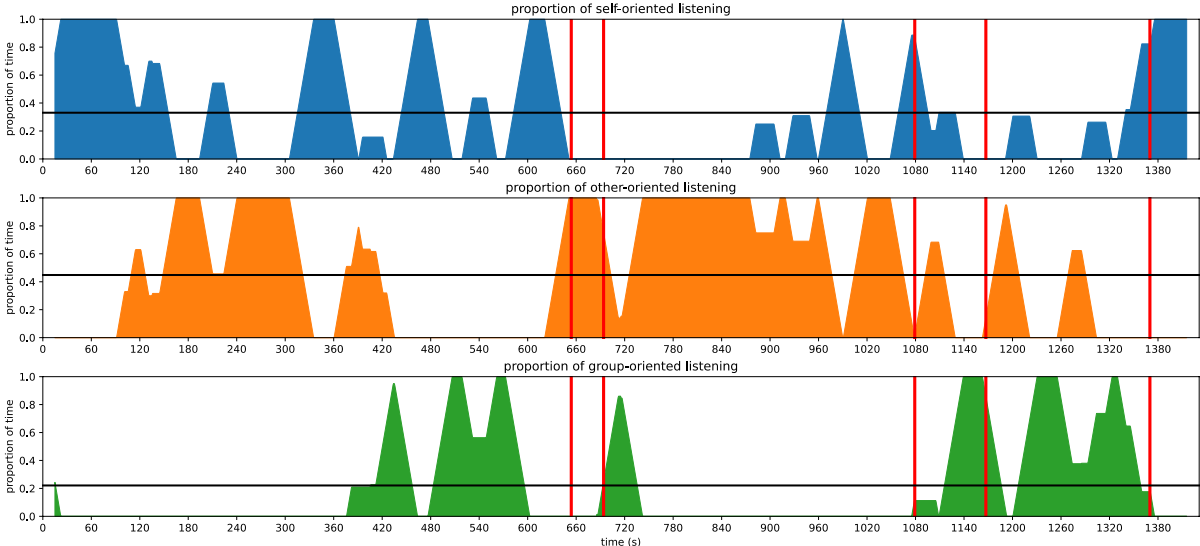
Figure 3. Proportions of each participant’s self-, other-, and group-oriented listening over the whole performance.



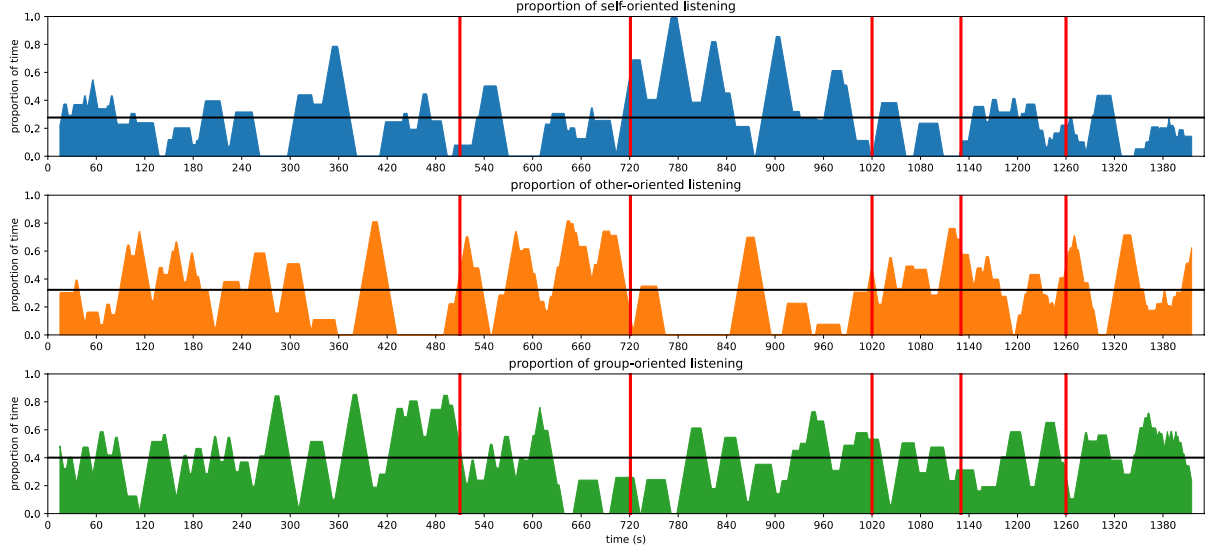
4a. CM



4b. IB

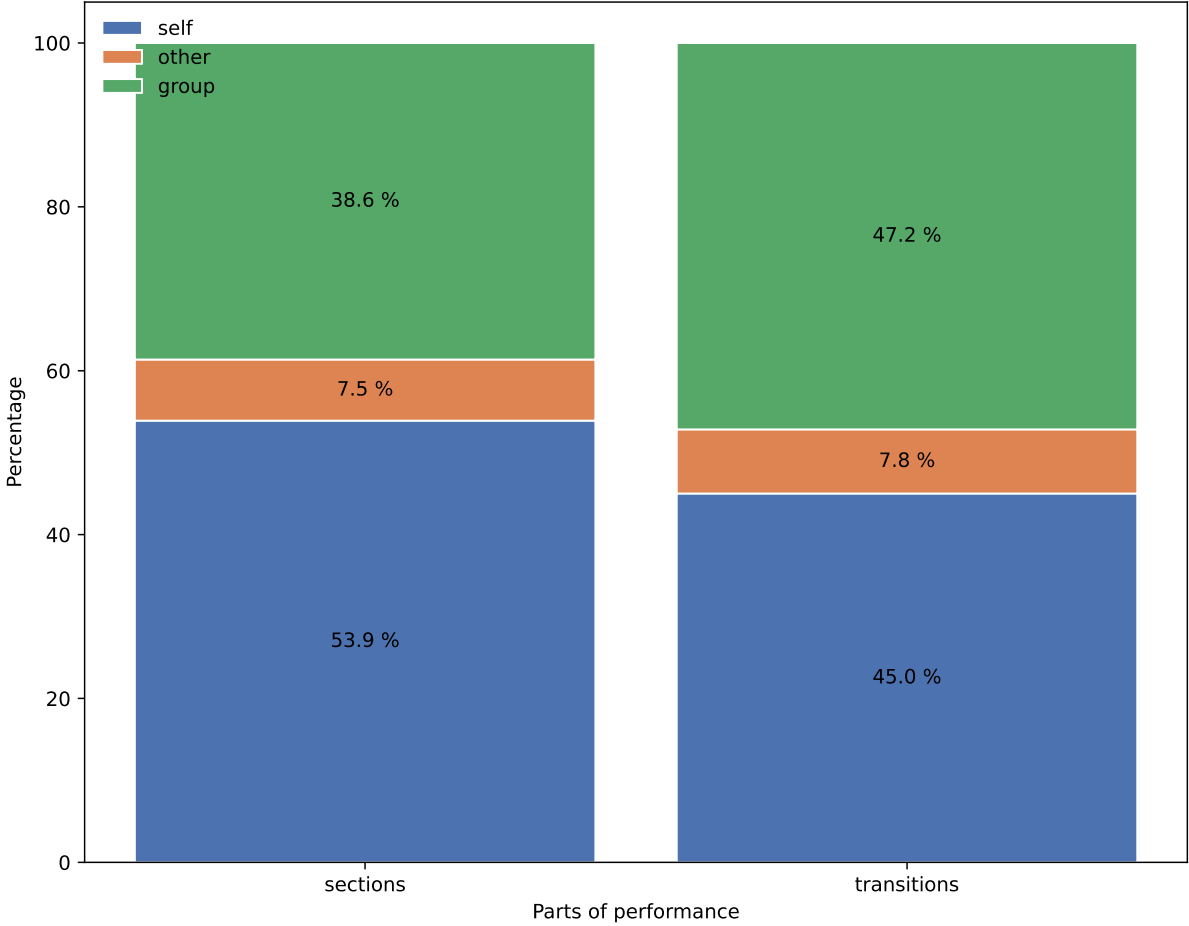


4c. AC

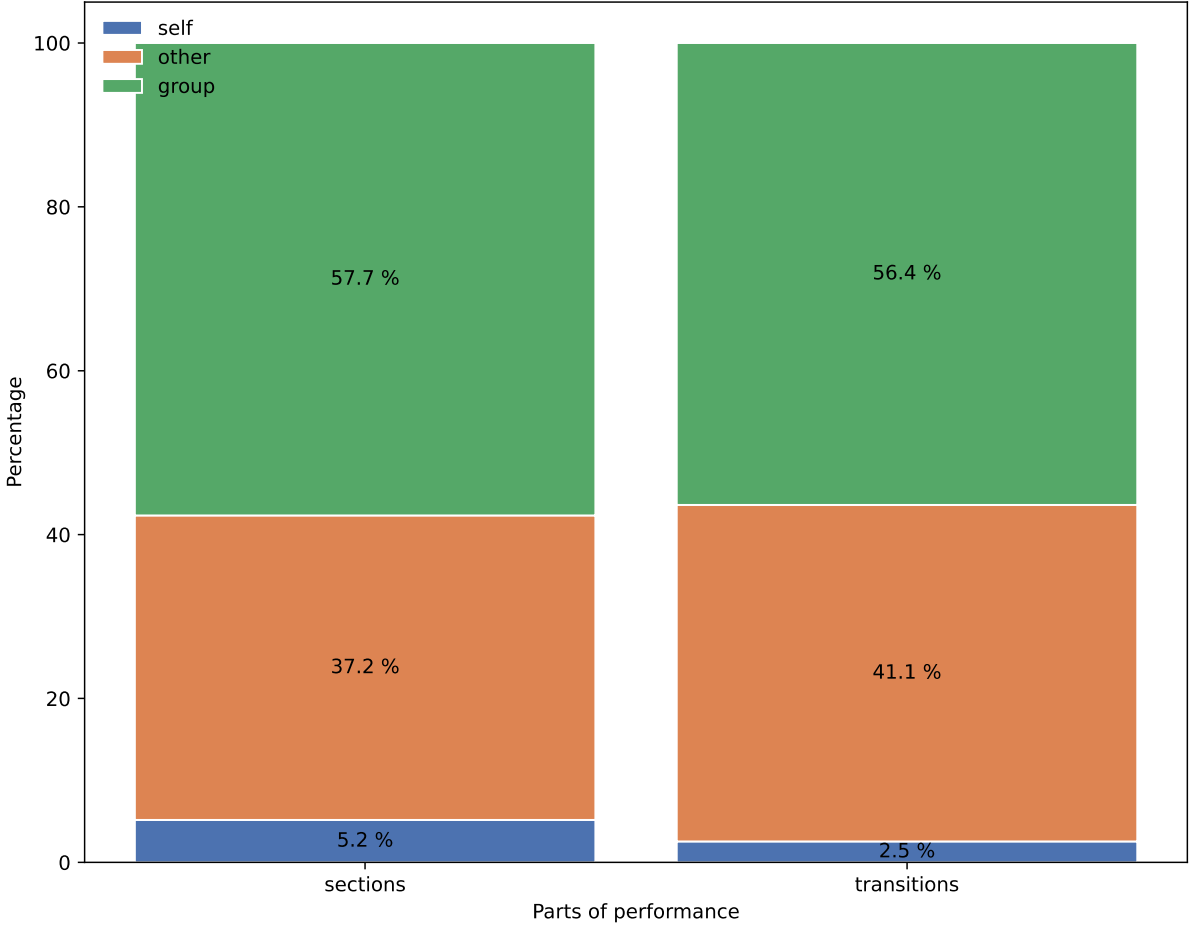


4d. SB

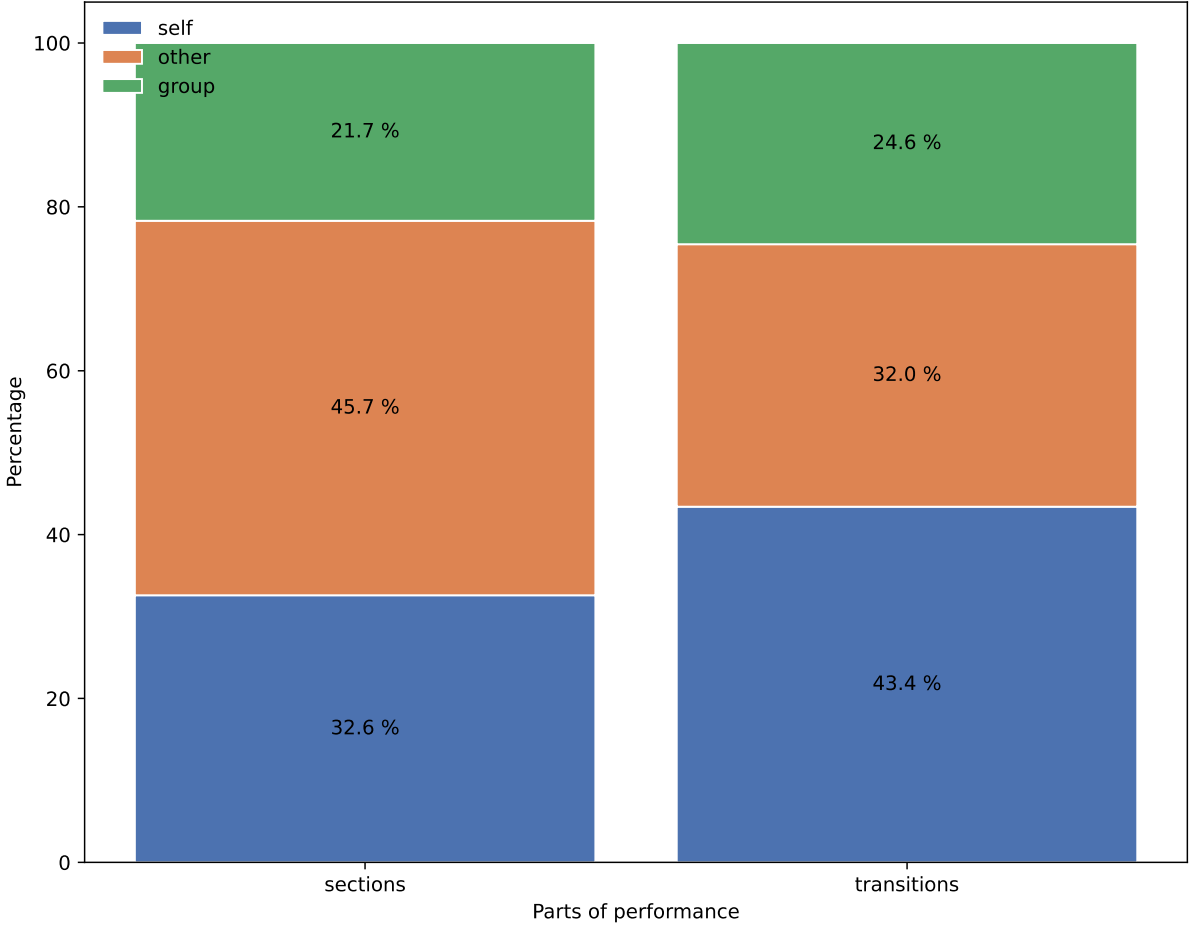
Figure 4. Proportions of self-, other-, and group-oriented listening in 30-second time windows for each participant. In each graph, red vertical bars show the participant’s own segmentation of their performance of Radigue’s work (cf. Table 1), and the black horizontal bar shows the average proportion of the corresponding listening orientation over the whole performance (cf. Figure 3).



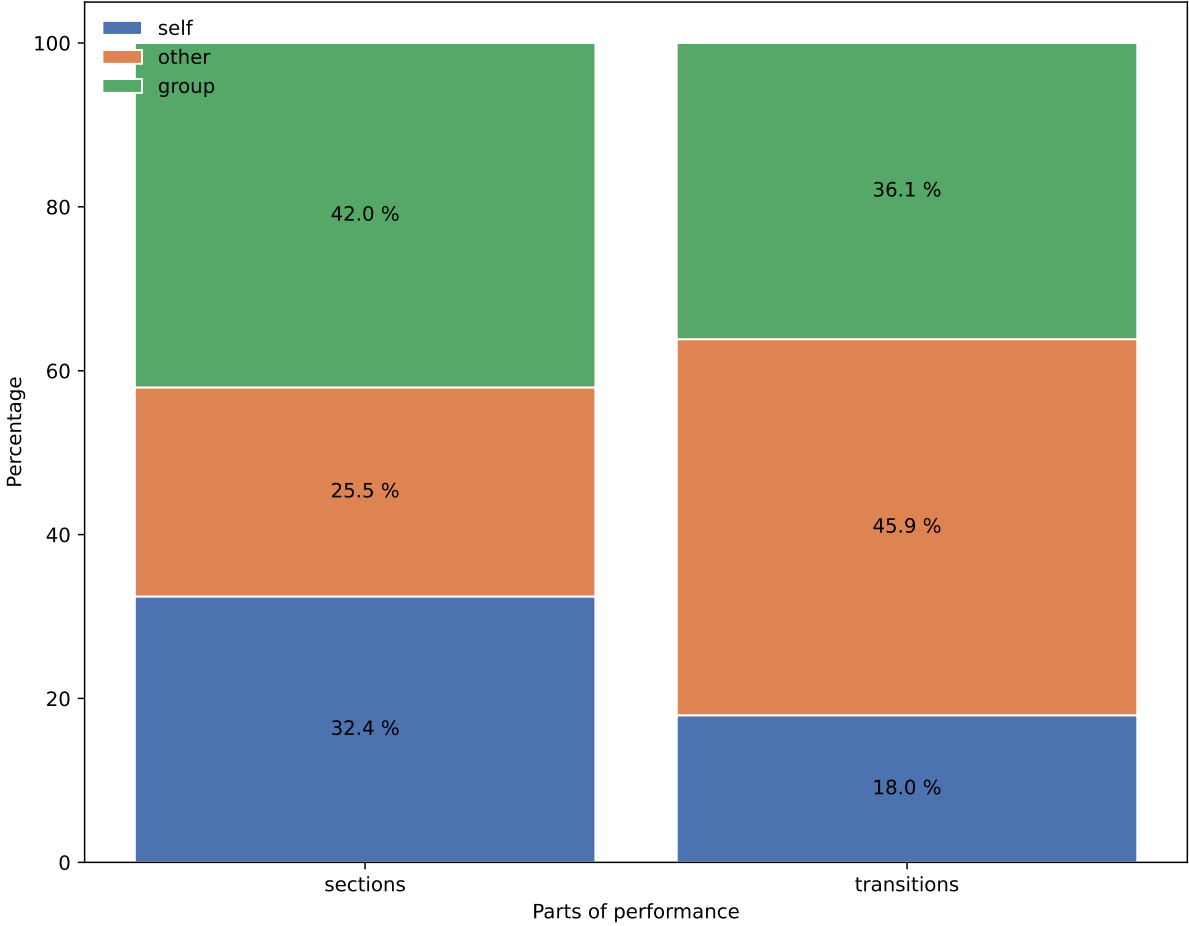
5a. CM



5b. IB



5c. AC



5d. SB

Figure 5. Proportion of self-, other-, and group-oriented listening during sections and transitions according to each participant’s segmentation of the performance (cf. Table 1).

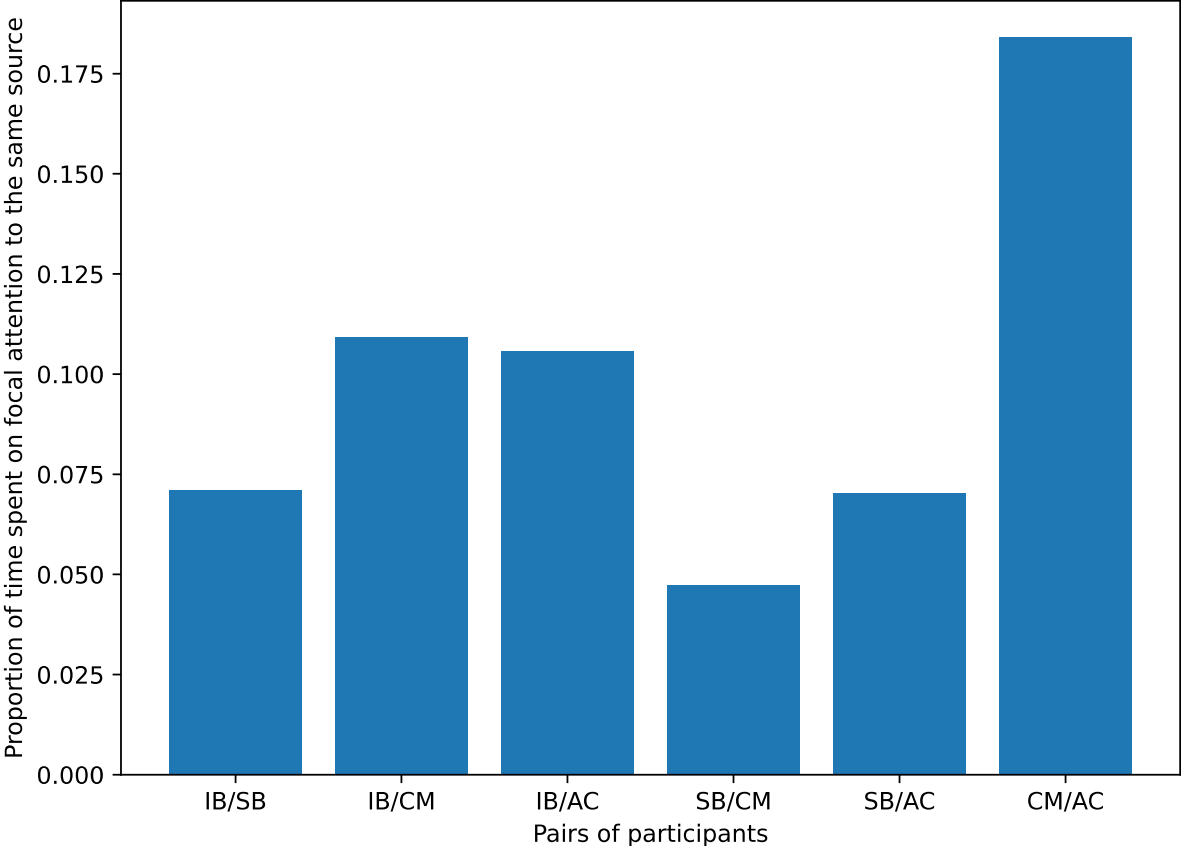


Figure 6. Proportion of time spent by each pair of participants on focal attention to the same source.

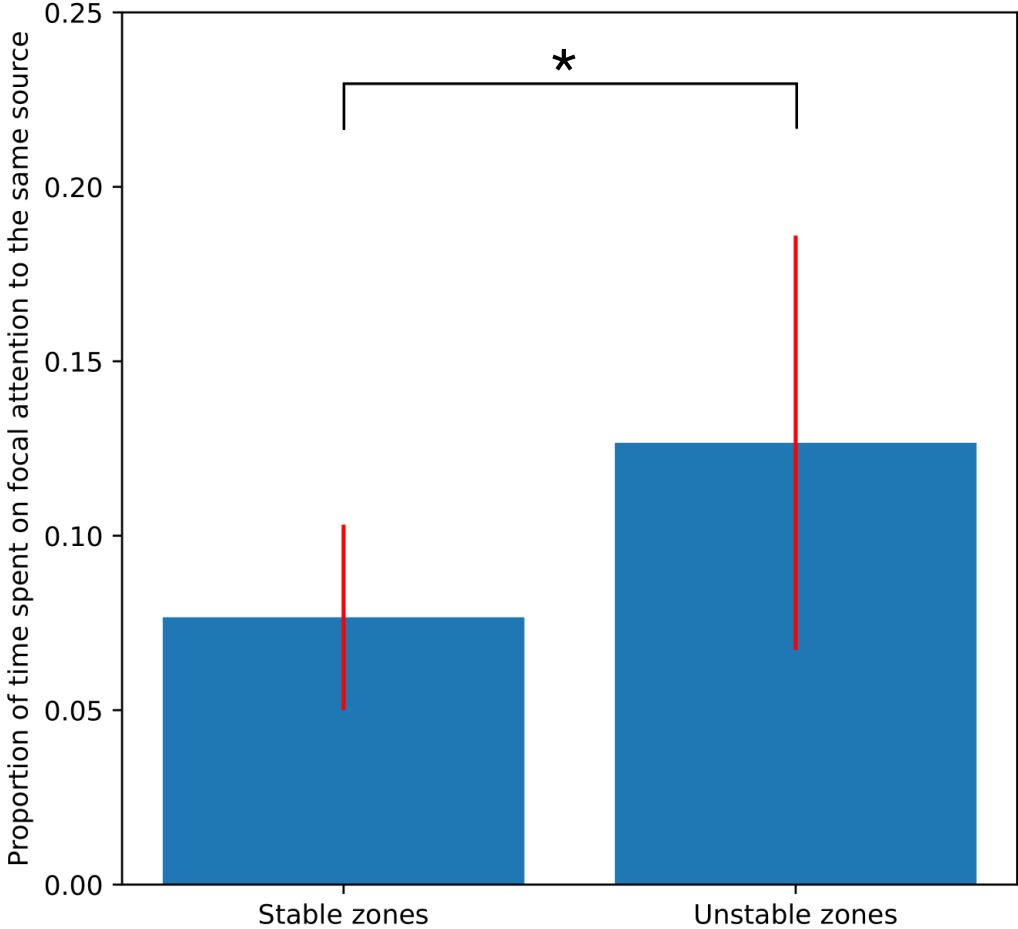


Figure 7. Proportion of time spent by participants on focal attention to the same source during stable and unstable zones. Error bars show standard error (95% interval), and the black asterisks shows a significant difference ($p < .05$).

The empirical study of the processes and mechanisms underlying joint musical performance has gained a lot of traction in the past few decades (for an overview, see Wöllner & Keller, 2017). In particular, many empirical studies have been dedicated to studying how musicians' visual attention, as evidenced, for example, by their gazing behavior (Kawase, 2014) and bodily gestures (D'Ausilio et al., 2012; Bishop & Goebel, 2018; Moran et al., 2015), might contribute to coordination and communication in joint musical performances. Furthermore, several mainly qualitative studies relating to musicians' more general state of awareness and focus of attention in joint musical performances have supplemented the above-mentioned gestural or visual-based empirical studies. For example, researchers have investigated whether or not an ensemble is empathetically attuned, aiming to shed light on the way modes of communication and interactional strategies within an ensemble, such as verbal communication, eye contact, and body language, might be influenced by its members' shared social and musical experiences and their familiarity with the conventions of a particular music genre (Seddon, 2004; Seddon & Biasutti, 2009). Similarly, Waddington (2017) points to moments where ensemble musicians speak of "achieving a collective state of mind" (p. 230), asking how this state of mind—which she also relates to empathy—might help understand group dynamics in small ensembles, and its potential role in facilitating co-performer interaction. Kaastra (2020) describes musical activity as a "highly dynamic and collaborative process invoking tacit knowledge and coordination as musicians identify targets of focal awareness for themselves, their colleagues, and their students" (p. 29) and connects musicians' shifts of focus to the "success" of their performances (p. 230).

A common feature of studies of collaborative attunement, co-performer empathy, and focal auditory attention is that they are largely qualitative, whereas studies of gestural and visual cues in performance are largely quantitative. It remains surprising that although research has been conducted on musicians' ability to divide their attention between their own actions and those of others, and to engage in simultaneous self-other integration and segregation (Keller & Burnham, 2005; Loehr et al., 2013), so little quantitative research has been conducted on musicians' listening strategies, when so much of the information relevant to their coordination is still conveyed through sonic—rather than gestural—means (Bishop et al., 2022). In particular, while research on the so-called cocktail-party effect (Cherry, 1953) is

still thriving (Swaminathan et al., 2015), comparatively little research has explored the distribution of musicians' auditory attention to each of their various co-performers, individually or in combination, or the factors that might underlie such processes.

There are obviously methodological reasons for this, as it is not clear how musicians' directional listening—and the source(s) of sound they select as their main focus of auditory attention—could be tracked dynamically during the course of the performance in the same way that visual attention can be monitored by eye-tracking devices. There might also be reasons related to the nature of the music used in most studies of joint music-making, which is typically notated in the form of a score, and well-rehearsed. In such contexts, the distribution of musicians' auditory attention is likely to be guided for the most part by the structure of the music as indicated by the score (e.g., the melody) or the meeting of goals that have been agreed during rehearsals, such as a particular desired sound. However, in less scripted, more open-ended musical practices, the chosen distribution of musicians' auditory attention is an integral part of interactional dynamics, and plays a crucial role in shaping how the performance will unfold. In the words of the jazz drummer Leroy Williams:

Although hearing everything over a musical journey represents the ideal, listening is typically a dynamic activity and performers continually adopt different perspectives on the musical patterns that surround them . . . Moreover, improvisers sometimes deliberately shift focus within the music's dazzling texture to derive stimulation from different players. (Berliner, 1994, p. 25)

Here, Leroy Williams refers specifically to jazz improvisation, but his insights can clearly be extended to the many musical practices that involve collective improvisation at least to some extent—in the sense that a significant part of the musicians' playing decisions have to be made during the course of the performance and that crucial aspects are negotiated as the music unfolds—and to the performances of compositions that are in- or largely under-determined, such as those for which the performers are provided with a broad and loose script. Williams highlights two ways in which musicians in these contexts might use listening as a creative resource: first, by listening to different aspects of the music (*aspectual* listening, e.g., focusing in turn on its timbral and rhythmic properties); second, by listening to different co-performers (*directional* listening, e.g., focusing in turn on the pianist and double bassist).

In this article, we report an exploratory empirical study designed to investigate directional listening in more open-ended musical practices. While directional listening does not exhaust the rich listening experiences musicians may have when jointly performing, it is still an important component of their activity, as illustrated above. Moreover, while it may be difficult to operationalize aspectual listening (there are many different ways to listen to a given sound, and a repertoire of listening modes might be shared only partially between the members of a given group), it might be easier to operationalize directional listening, and it therefore seemed to us that studying directional listening would constitute a reasonable first step in the exploration of the much wider territory of “listening-while-performing” (Clarke, 2005, p. 152).

For this study, we chose to focus on Quatuor Bozzini (QB)’s performance of *Occam Delta XV* (2018) for string quartet by Éliane Radigue. For the past six decades, Radigue has dedicated herself to creating a work in which natural microbeats between frequencies arise from continuously sounding tones, replacing rhythmic or other more traditional forms of sound organization. In performance, Radigue’s works often start with a clear fundamental, or first harmonic. This fundamental is eventually forgotten in favour of resulting pitches such as harmonics, sub-harmonic or Tartini tones, and the micro-vibrations that emerge from them (Eckhardt, 2019; Girard, 2013). The organization of Radigue’s compositions thus stems, in a way, from the sound itself. Temporality and form are no longer understood as constituting an external structure imposed by the composer on her work, but rather as inherent, emergent, and inseparable from the internal activity of sound (Majeau-Bettez, 2017). To a certain extent Radigue’s music is comparable to that of Giacinto Scelsi, insofar as Radigue’s largely intuitive work focuses on the inner activity of sound (Amblard, 2009). Her approaches to sound also resemble those of her American minimalist colleagues, Charlemagne Palestine, Phill Niblock and, above all, La Monte Young, who helped to establish musical minimalism (Potter, 2020). Her music differs, however, from the minimalist drone pieces by Niblock and Fullman, for example, in that it includes harmonic changes (Girard, 2013).

Radigue used the ARP 2500 modular synthesizer to compose most of her works for four decades. Since 2001 she has collaborated exclusively with performers using an oral mode of music transmission in which chord progressions, pitches, and the duration of the work are not specified in advance. QB contacted Radigue through mutual friends and colleagues to let

her know they were interested in her music and her approach to composition. She worked with them for three days in 2016 and again in 2017 before QB gave the first public performance of *Occam Delta XV*; since then, they have performed it 11 times.

Occam Delta XV offers a particularly interesting example of the kind of works Radigue has been producing in recent years, which are characterized by a high level of indeterminacy. The members of QB have often spoken about the implications of indeterminacy for the way they learned *Occam Delta XV*. Remembering their first rehearsals with the composer, the cellist Isabelle Bozzini said, “we all had a different idea of where the different parts were, and what we should do or not do.”¹ In what follows we attempt to clarify the effect of indeterminacy on the dynamics of QB’s auditory attention while performing Radigue’s music.

First, as is typical of Radigue’s compositions for acoustic instruments, *Occam Delta XV* is indeterminate in that it has no score. Rather, the composer gives the performers verbal instructions during rehearsals. Sounds are not organized as chords or rhythms; instead, the work is loosely based on the image of a large body of water that narrows in the middle of its course before broadening out as it *approaches the ocean*.² It is thus in three sections but the musicians must decide how to make the transition from one to the next and when to do so in performance. They are encouraged to apply her interpretation of William of Ockham’s razor: simplest is always best. If they feel a section is going well they should sustain it. If not, they should start making a transition to the next section immediately. In no circumstances should they force the sound material. The duration of each section of the work in a given performance will thus depend on how well the performers feel it is going and therefore how quick or slow they are to move from one section to the next. This in turn will depend on factors such as their level of concentration and the resonance of the hall. In short, performances of *Occam Delta XV* provided the opportunity to find out how musicians’ listening guides their collective navigation of the work, given its open-ended nature.

¹ Unless otherwise indicated, all quotations (translated by the authors) are from the recordings of the sessions that took place at Radigue’s apartment on July 11th, 12th, and 13th, 2017, at which the first author was present. She has also made video- and audio-recordings of most of QB’s performances since 2018. These recordings pre-date the study reported in the present paper.

² Radigue uses water images to structure her works and organize them into sections.

Second, *Occam Delta XV* is indeterminate in that roles such as leader and follower, responsible for melody or accompaniment, are not assigned to members of the quartet, because they are intended to contribute equally to the always-evolving overall sonic texture. QB learned to play Radigue's music through her oral transmission of this work:

Éliane Radigue (ER): You must already know it [the sound material] if you know my work—is essentially a work on partials, on overtones, on micro beatings, on pulses, on harmonics, on subharmonics. To obtain these, there is no need to [use fermatas] or to suspend the beat, because there is no beat! Of course, everything is in *piano* dynamics, from *ppp* to—sometimes a *mezzo forte* (more *mezzo* than *forte*!) because when it's too loud, that's when the fundamentals resurface. That's that for the technical work. For the tuning—and this is more valid for the solos—we couldn't care less about the tuning fork. 440 or 435 *on s'en fiche*! And even when playing in quartet, there can be very, very slight variations [in tuning], and that's actually what creates—between the instruments—all these little intangible, elusive marvels. Subharmonics are rare, *rarissimes*! Do you guys ever produce some? They are low pulses, completely immaterial . . . but wow! When we hear it, wow!

Isabelle Bozzini (IB): I never produced one when playing alone. When we play together sometimes . . .

ER: This is the material with which we are working. There are never brutal attacks . . . there must be a continuity.

Radigue rarely commented on issues of technique in rehearsals, beyond those illustrated above; she only referred to bowing once (“From what I have seen, between the bridge and the tailpiece, it is often very interesting. This is just from what I have seen because I am no violinist!”) and did not mention the use of one or more strings, or what and when the musicians should play. As the experts on their instruments, they had to figure this out for themselves. During the process of oral transmission, Radigue went shopping for sounds, as she described it: “Yes, this I like. No, this I don't buy.” Thus, for QB, learning *Occam*

Delta XV involved learning how to play the music of Radigue in general, rather as one learns to ride a bicycle and can then choose where, when, and how to ride. Their performances of the work provided an opportunity to find out how musicians' listening might regulate their individual contributions to the production of the collective, complex, sonic texture so typical of Radigue's aesthetic.

Third, *Occam Delta XV* is indeterminate in that, from a phenomenological perspective, it demands of the performers a high degree of loss of self. The members of QB often play more or less the same notes when performing music by Radigue, but a few cents apart. When the two fundamentals are sustained, an interference pattern progressively appears between them that is perceived as beating (Meyer, 1957, pp. 646-50), or even as an extra note known as a difference or Tartini tone (see <https://www.animations.physics.unsw.edu.au/jw/beats.htm>). These tones accumulate in Radigue's music to evoke the image of a large ball of sound floating in the air during the performance, according to the clarinetist Carol Robinson (personal communication, 2017). During performances it can become increasingly difficult to distinguish the notes that are played and those that emerge from the encounter of slightly different frequencies:

Clemens Merkel (CM): With the mix [of sounds] I can't know anymore.

IB: It's like an accordion!

CM: At one point there was a beating between Isabelle and I, so I tried to play with my pitch a little. But then it wasn't me at all! That's what's most difficult—knowing which note to play! I don't know who is playing what, so then I don't know how to react [laughs].

This is particularly salient as, unlike the other ensembles who perform Radigue's music, QB play the same family of instruments. Thus performances of *Occam Delta XV* provided the opportunity to carry out a case study in which we sought to discover how musicians use listening to assess their sense of self in a sonic context in which the frontier between self and other is indeterminate.

For all these reasons, *Occam Delta XV* provides a highly relevant case study to investigate the dynamics of musicians' auditory attention in an indeterminate musical context and to better understand the listening strategies that underlie their coordination.

Methods

Participants

The four members of QB—the dedicatees of *Occam Delta XV*—were recruited as participants in the study, and gave their written consent to do so. QB is a Montreal-based string quartet founded in 1999, specializing in new, experimental, and classical music. It comprises Isabelle Bozzini (IB) (cello), Stéphanie Bozzini (SB) (viola), Alissa Cheung (AC) (violin), and Clemens Merkel (CB) (violin). IB and SB have been performing together since childhood. CM joined the quartet in 1999, and AC in 2005. There is no definite first or second violin position within the ensemble. Depending on the type of repertoire, AC and CM play the violin parts interchangeably. They typically play more than 50 concerts each season (21 to date) in Quebec and internationally. They have had over 150 collaborations, many of them long-term, with performers, young composers, established artists, and choreographers. They have commissioned nearly 200 works and premiered more than 300 (Quatuor Bozzini, 2022).

Over the past two decades QB have become specialists in the slow, very soft music typical of Radigue, where “silence occupies a large share of its often extended performance duration” and in which “harmony, rhythm and melody play either a subordinate role or none at all” (Melia & Saunders, 2011, p. 445–448). Since 1999 QB has promoted the composers of the Wandelweiser collective, being among the first to play the works of Jürg Frey, Antoine Beuger, Burkhard Schlothauer, and Michael Pisaro. Its most recent work with contemporaries of Radigue including Alvin Lucier, Phill Niblock, and Pauline Oliveros, all considered pioneers in the genre, testifies to the durability and importance of this type of experimental music in the repertoire of the quartet.

Procedure

First, we asked QB to perform *Occam Delta XV*. The performance took place in a studio at IRCAM (Paris) and was recorded by a professional sound engineer who had worked

with QB before and could therefore produce a stereo recording that accurately reproduced their live sound. Immediately after the recording, the ProTools session was bounced without any additional mix to produce a WAV file. The bouncing and export took roughly five minutes. We then asked the participants to listen to the recording of their own performance on an iPod, through headphones, and use a web application on the same iPod to make their annotations (see Figure 1). The web client, running in a regular web browser, was connected to a server through a bidirectional and persistent communication channel to send and store annotations on the server in real time as well as to provide information to the researchers through a remote monitoring panel (Matuszewski, 2019).

[Insert Figure 1 here]

The participants used a graphical user interface (GUI) in the shape of a square that mimicked the quartet spatial positioning when performing. Importantly, as can be seen in Figure 1, the GUI had no labels: it was meant to be used indexically, with the bottom corner referring to the annotating musician, the upper corner to the musician seated in front of the annotating musician, and so on. We provided the following written instructions: “As the recording is playing, please indicate what your main focus of attention was at each moment of the performance:

- If you were mainly listening to your own sound, drag the cursor to the bottom corner of the square;
- If you were mainly listening to the sound of the musician to your left, drag the cursor to the left corner of the square;
- If you were mainly listening to the sound of the musician to your right, drag the cursor to the right corner of the square;
- If you were mainly listening to the sound of the musician in front of you, drag the cursor to the upper corner of the square;
- If you were mainly listening to the overall sound of the quartet, drag the cursor to the center of the square.”

These instructions were designed to emphasize that participants should use the recording not to report what they were hearing but rather to elicit recall of their listening orientation while performing, drawing on previous research in music performance studies (e.g.,

Ponchione-Bailey & Clarke, 2022). We used a GUI rather than collecting verbal reports because, first, this has been used successfully in recent studies on improvised musical practices to gather data on performers' higher-order intentions, such as to change or maintain the direction of music produced by the group (Goupil et al., 2020), or converge with or diverge from their duo partner (Golvét et al., 2021). In a slowly evolving work such as *Occam Delta XV*, in which performers are challenged to adjust their pitches to each other to produce the desired beating effect, we assumed that listening orientation would be a salient aspect of the participants' experiences and, as such, should be reasonably available to their introspection and recollection. Second, as revealed by the first author's ethnographic work since 2017, the participants did not speak readily about Radigue's music, having played *Occam Delta XV*, or how their auditory attention evolved while playing it. When asked how they listen to each other or transition from one section of the work to another, they typically chuckle, shrug, and say, "We don't know!" (CM, personal communication). Neither do they discuss it among themselves as they might the performance of a notated piece, for example, "It's not like in a Mozart quartet where you'll say, well, the second movement was a little too fast! [laughs]" (CM, personal communication). Rather, performing the music of Radigue is a deeply introspective act: "When we play, in some ways we are aware that there are people in the audience, but when we finish it's always difficult to get back 'out'" (CM, personal communication). Interviews concerning auditory attention, particularly those conducted even just a few hours after a performance, having yielded insufficient data, we replaced the first author's ethnographic approach with the post-hoc method described here. Third, the use of the GUI enabled us to gather data from the four participants simultaneously as soon as the performance had taken place, comparing their four listening orientations with each other and with the details of the music as it evolved. This represented a further advance on the use of verbal reports, as these tend to differ from one performer to another, focusing on remarkable episodes, and leaving the researcher to make sense of gaps during which the performer has not accounted for their behavior (for other concerns on verbal protocols, see Ericsson & Simon, 1998).

Once this first task had been completed, and after a 10-minute break, we asked the participants to listen again to the recordings of their performances and segment them as follows: "Please write down the timings corresponding to:

- The moment you started to go to the second section;
- The moment you had definitely reached the second section;
- The moment you started to go to the third section;
- The moment you had definitely reached the section part;
- The moment you started looking for an end to the performance.”

Using iTunes as a media player, and pen and paper, each participant thus segmented the performance into six parts (i.e., Section 1, Transition 1, Section 2, Transition 2, Section 3, Transition 3) corresponding to their own navigation of the loose structure of the work. They could pause the recording or rewind it at any time, and were asked to write down the timings of the beginnings of each part only when they were reasonably confident in their answers.

Data pre-processing

We pre-processed the annotation data by linearly interpolating positions on the interface between time points with a resolution of 4 Hz. This value was chosen because it was sufficiently low to capture most of the participants' movements in the interface, and sufficiently high to reduce the size of the dataset for the analysis.

Figure 2 provides a synopsis of the annotations indicating the location of each participant's main focus of auditory attention at each moment. A video showing the annotations synchronized with the recording of the performance is also available [here](#).

[Insert Figure 2 here]

Variables

We computed the following set of variables to investigate the participants' listening orientations and their temporal dynamics.

First, we categorized listening strategies as self-oriented or other-oriented to one other participant (*focal attention*) or the group as a whole. For each musician, we thus computed the amount of self-oriented listening (amount of time the musician is listening to themselves), the amount of other-oriented listening (amount of time the musician is listening to another quartet member), and the amount of group-oriented listening (amount of time the musician is listening to the overall sound of the quartet). These variables were computed on a global scale

(i.e., the overall performance), but also on a finer scale (using 30-second windows), in order to be able to track how musicians' listening orientation developed over the course of the performance. We considered this length of time appropriate because *Occam Delta XV* is a slowly evolving piece of music: averaging over 30-second windows allowed us to grasp the temporal dynamics of participants' listening orientation quickly without losing too much relevant information.

Second, for each pair of participants, we computed the durations of focal attention to the same source (i.e., a member of the quartet).

Third, for each pair of participants, we delineated stable and unstable zones (i.e., when two participants were in the same part of the work, such as Transition 1, and when they were in different parts, such as Transition 1 and Section 2). This allowed us to assess the extent to which auditory attention varied as a function of participants' coordination dynamics (i.e., if they were all in the same part or different parts of the work).

Results

Segmentation

Participants began transitioning from one section to the next at different times, as shown in Table 1. Except for the last transition to the end, CM was always the first to start a transition and to reach a new section; for example, he started transitioning to the second section at 4 min 58 s, almost six minutes before the last participant, AC. He felt he reached it at 7 min 15 s, roughly five minutes before SB, who did not reach it until 12 min 10 s. CM started transitioning to the third section at 13 min 18 s, almost five minutes before AC, and reached it at 15 min 27 s, four minutes before AC. Except for the moment when participants felt they had reached the start of the second section, AC was always the last member of the quartet both to start a transition and settle into a section.

Table 1. Participants' segmentation of *Occam Delta XV*

	IB (cello)	SB (viola)	AC (violin)	CM (violin)
To 2 nd section	8 min 30 s	8 min 30 s	10 min 54 s	4 min 58 s
Reached 2 nd	10 min 20 s	12 min 10 s	11 min 54 s	7 min 15 s

section				
To 3 rd section	14 min 02 s	17 min 0s	17 min 59 s	13 min 18 s
Reached 3 rd section	15 min 54 s	18 min 50 s	19 min 27 s	15 min 27 s
Looking for end	21 min 08 se	21 min 0s	22 min 50 s	22 min 05 s

Individual listening orientations

As shown in Figure 3, there were differences between the proportions of time spent by participants on self-, other-, and group-oriented listening during the whole performance.³ For example, CM spent 51.6% of its duration on self-oriented listening and 40.8% on group-oriented listening, while IB spent only 4.5% on self-oriented listening, 38.2% on other-, and 57.3% on group-oriented listening. By contrast, AC spent 43.9% on other-, 34.0% on self-, and 22.1% on group-oriented listening, while SB spent 40.0% of the whole performance on group-, 32.5% on other-, and 27.5% on self-oriented listening.

We then compared each participant's listening orientations over the course of the performance with the sonic and musical structure of the work,⁴ as shown in Figures 4a-d. In each figure the top, middle, and bottom graphs respectively show the proportions of time spent in 30-s time windows, on average, on self-, other-, and group-oriented listening.

³ As we specified to participants, we do not consider self-, other-, and group-oriented listening as mutually exclusive categories, taking for granted that participants listen in all three ways simultaneously but with different levels of attention.

⁴ Having listened to the recording of QB's performance of *Occam Delta XV*, the first author has provided the following description. "The performance started at a *mezzo piano* dynamic. In the first minutes of the work the string players' individual sounds were heard most discretely in the mix of sounds. At c. 120 s, the resulting tones typical of Radigue's music started to build up, and the quartet sounded more like one breathing instrument. At c. 240 s, there was a dip in the sound; CM had already started transitioning to the second section of the work. In response to the segmentation task he reported that this was one of the hardest parts of the performance; the transition implies breaking away from the 'initial state' of the work and moving towards 'other harmonies and registers.' In general, this second part presents the most fragile sound material: the quartet moves to a *piano* dynamic, they play harmonics, the pitch range is narrower, and the resulting tones build up and make it extremely hard to decipher individual instruments. This new section emerged at c. 420 s, with CM playing more softly as he switched to harmonics (his sound was the most audible on the recording, although not to QB in performance). At c. 780 s, the sound became louder as the quartet began their transition to the last section of the work, which was reached at c. 1080 s. Here the quartet had begun to play fundamentals and the pitch range had become even wider. At c. 1200 s, the final, most coordinated transition took place; there was a clear change in harmony, and the texture thinned out."

[Insert Figure 4 here]

IB and CM both maintained stable listening orientations. IB alternated between other- and group-oriented listening, with a slight surge in self-oriented listening towards the end of the work at c. 1090 s. This increase in IB's self-oriented listening took place as she and SB led this section at c. 1260 s. Similarly, CM's use of self-oriented listening appears to be linked to his leading of all but one of the transitions. His listening was group-oriented before he started his first transition at c. 240 s and self-oriented as soon as he had completed it at 300 s; a similar pattern can be seen at all other important points in the narrative, according to his segmentation: group-oriented at c. 330 s, 780 s, and 1170 s; self-oriented at c. 360 s, 810 s, and 1290 s. His rarer use of other-oriented listening corresponded to important points in the other participant's performance; for example, at c. 600 s to IB and at c. 720 s to SB settling into the second section. The only transition not led by CM was the one towards the end and at that moment his listening became group-oriented.

By contrast, SB and especially AC's listening orientations tended to correspond more to the narrative of the work. AC's listening was self-oriented for the first two minutes, alternated between self- and other-oriented for the next five minutes, and group-oriented towards the end of the work. She used self-oriented listening to a lesser extent at important points in the narrative, for example using other-oriented listening at c. 660 s when she transitioned to the second section and group-oriented listening at c. 690 s when she settled into it. Similarly, she used less self-oriented listening as she transitioned to the third section and then more other-, and finally more group-oriented listening. Her listening was other-oriented when she reached the third section. SB's listening orientations were similarly varied. She used all three orientations for very short periods in the first two minutes but extended them to c. 30 s from c. 150 s. She was least likely to use self-oriented listening during transitions, preferring other- and, to a lesser extent, group-oriented listening.

The analysis of these data representing participants' listening orientations complement the largely unsatisfactory questionnaire and interview data. For example, we asked participants in a questionnaire administered c. 30 mins after the performance who had directed each of the transitions. As shown in Table 2, none took individual responsibility but

attributed it to one or more of the other participants. But the annotation data in fact revealed otherwise.

Table 2. Participants' responses to the questionnaire item "I had the impression that [name (s) or role (s)] directed the transition."

	IB	SB	AC	CM
Transition 1	No one in particular	IB	CM	IB
Transition 2	Violins	Another member [of QB]	IB	No one in particular
Transition 3 (to the end of the work)	No one in particular	Another member	Another member	Another member

Differences between participants' listening orientations in sections and transitions

As shown in Figure 5a-d, all the participants except AC spent more time on other- and group-oriented listening than self-oriented members during transitions. This is likely to be attributable to the need for musicians to adjust their own behaviour to that of their co-performers as it evolves, and suggests that they use attentional focus to enhance coordination with others.

[Insert Figure 5 here]

Focal attention to the same source

As shown in Figure 6, focal attention to the same source (i.e., another participant) varied between pairs such that CM and AC spent 18.4% of the duration of the performance on other-oriented listening to the same source while CM and SB spent only 4.7% on it. The highest amount of focal attention to the same source was thus observed to be between the two violinists, which might be to the specific coordination problem these two musicians have to face, given that they share the exact same range and timbre.

Additionally, as shown in Figure 7, focal attention to the same source was more frequent in unstable than stable zones. A paired *t*-test confirmed that the proportion of time spent with focal attention to the same source was larger in unstable ($M=0.13$, $SD=0.06$) than stable zones

($M=0.08$, $SD=0.03$, $t(5) = -2.7$, $p=.04$). This suggests that focal attention to the same source is more likely to emerge in situations in which the coordination between musicians is more challenging.

[Insert Figure 6 here]

[Insert Figure 7 here]

Discussion

Our study shed light on how the auditory attention of musicians relates to their interactional dynamics during the performance of indeterminate music such as Radigue's *Occam Delta XV*. First, for this performance at least, there was a clear distribution of roles within the quartet, linked to the idiosyncratic listening strategies of its members. This was not evident in the numerous interviews conducted by the first author with QB during rehearsals.⁵ Asking the participants to record their attentional focus revealed how they interacted with one another. Listening and interacting are tightly connected in collective settings, but they are nonetheless distinct aspects of musicians' performing behavior. For example, focusing on one's own sound does not necessarily mean that one is playing without reference to other players; rather, to be able to play as independently as possible from the other musicians, one might need to listen to them carefully (Golvét et al., 2021). Here, we were struck by the links between listening strategies and relationships between the participants. The listening orientations of both CM and IB marked them as leaders albeit in different ways. Rather than following the leads of others, CM divided his time largely between self- and group-oriented listening, not only initiating all except the final transition but also listening like a leader, focusing on the sound of others only once he had made a transition himself. His listening strategy thus marked him as leader in terms of the timing of transitions and therefore the

⁵ This is in part due to the participants' mental state while and after performing *Occam Delta XV*. According to CM, it is a deeply intimate and introspective act to perform the music of Radigue's music and therefore difficult to speak about with audience members or even among themselves, let alone to respond to questions as to how or to whom they listened during the performance.

unfolding of the work as a whole. Yet IB was also a leader; the work's narrative being built on the tension between fundamentals and higher harmonics, the low register of the cello conveys great authority in the texture and, consequently, the dramatic structure of the performance. We can therefore interpret her other- and group-oriented listening as indicators of her role as leader in the textual and timbral development of the work, and as a leader-supporter within the dynamics of the ensemble. The listening strategies of AC and SB were more flexible than those of CM and IB in that, for example, AC chose other-oriented listening when making important structural decisions and was almost always last to make a transition. Unlike CM, then, who listened only retrospectively to the other participants, AC did not make transitions until she had heard all the other participants do so, and she thus fulfilled the role of consolidator, confirming the narrative of the work. Likewise, SB's listening strategies and her timing of transitions indicate that she played a similar role, strengthening others' intentions as they reached a particular section of the work and reaffirming its dramatic contours. In sum, AC and SB acted as middle-women, so to speak, in the ensemble; they both reacted when CM had initiated a transition from one part to the next during the performance, and SB followed IB to confirm the decisions already made by the violinist and cellist.

To a certain extent, the roles played by the members of QB in this performance reflect the leader-follower roles identified in more traditional string quartet performances (Glowinski et al., 2012). It has been found that the members of string quartets occupy different—albeit exchangeable—leadership roles during a performance (King, 2006; Gilboa & Tal-Shmotkin, 2012). Although social and interpersonal relationships within the string quartet must be taken into account, the notated score of the work—with its main themes and their accompaniments—largely determines the role of each musician in its performance (Glowinski et al., 2012). Even though the musical material of *Occam Delta XV* is open-ended, and the participants often spoke from their own personal perspectives of the meditative or loss-of-self qualities induced by performing Radigue's music, our analysis of their listening orientations particularly during transitions shows that they nevertheless assumed traditional roles: CM the first violin, IB the supportive cellist, and SB and AC taking on the typical “relay” responsibilities of second violin and viola respectively.

This may seem surprising given the experimental sound material and arguably alternative structure of the work, but we can put forward two explanations. In the first place,

QB specializes in academic art as well as experimental music (Bozzini, 2022). It is a traditional string quartet insofar as much of their repertoire consists of canonical works in which, for example, main themes and accompaniments define the roles of the musicians. These are thus ingrained in the quartet's usual set of performance tools even when playing *Occam Delta XV*. In the second place, the sound material and structure of the work are such that it is “made of two real-note sections surrounding a harmonics middle part” (AC: personal communication). The importance of the fundamental in this kind of music, whether present or absent, gives the cello responsibility for texture and timbre, the two main structural elements of *Occam Delta XV*. The viola is required to blend with the cello, and the second violin between the viola and the first violin. The participants responded to this sound material as though the tension between the fundamental and the harmonics, producing new timbres and textures, were akin to the melodic themes and harmonic progressions of more traditional compositions for string quartet, requiring them to play traditional leader-follower roles. While the precise distribution of roles we observed was not arbitrary and can certainly be explained, it is not necessarily bound to persist every time QB performs *Occam Delta XV*. This distribution was never discussed explicitly by the participants: rather, the roles emerged spontaneously either during rehearsals or in the course of the performance as a way of solving specific coordination problems (see Saint-Germier & Canonne, 2020, for similar insights).

Second, participants' listening strategies helped them navigate the indeterminate temporal structure of *Occam Delta XV*. Despite their shared experience of performing the music of Radigue they nevertheless segmented the work in different ways and at their own pace, resulting in a performance including moments at which each participant was playing a different section or transition and moments of consensus when they were all, literally, on the same page. It is the ambiguity inherent in indeterminate music that makes it interesting for performers, as they can make numerous choices, either before or in the course of performance (Anderson, 2006; Payne & Thomas, 2022). We were struck in this study by the way participants adapted their listening strategies to the structure of the sounds that emerged from their decisions and behaviors. Musicians always listen actively during a performance, shifting their focus and level of attention to coordinate with each other. In the present study, participants paid more attention to their co-performers when they began to make a transition—in other words, when the coordination problem was mainly temporal, requiring

them to adjust to the movements of others. Conversely, they paid more attention to their own playing when they were playing within a more clearly-defined section—in other words, when the coordination problem was mainly spectral, requiring them to blend their own timbre with that of the others. Thus listening in performance involves more than merely picking up affordances from the sonic environment collectively produced by oneself and other musicians (Clarke, 2005; Windsor & De Bézenac, 2012; Saint-Germier & Canonne, 2020). In this case the participants also used auditory attention selectively depending on both interactional dynamics and the need for coordination.

Third, we found that joint focal attention to the same source might support coordination between musicians, as this occurred to a greater extent in unstable zones in which coordination was more difficult, given the divergences between participants' behaviors and representations, than stable zones, when they were more convergent. It may be that unstable zones contained more salient events attracting the attention of two or more participants to the same sound source and allowing them to coordinate more efficiently with one another. While general conclusions cannot be drawn from case studies, this finding nevertheless provides the first evidence (to our knowledge) of joint auditory attention as, so far, joint attention has only been studied in the visual modality, even in the context of collective music-making (Glowinski et al., 2012). Our study thus contributes to the understanding of the role of joint attention in supporting coordination during joint action (Vesper et al., 2017), confirming the intuition that “consensually attending to the overall ensemble sound or to a common subset of sounds” (Keller, 2008, p.211) improves coordination. It would be possible in future research to investigate more systematically the prevalence of various forms of joint listening (e.g., focal, aspectual) in score-based and improvised collective music-making, to discover the extent to which it supports coordination. Post-hoc annotation procedures such as those used in the present study could be used, or performers could be asked to follow a pre-established script alternating convergent and divergent attentional behaviors. This would help to establish joint attention as a general cognitive process underlying joint action in a wide variety of settings and extending beyond the visual domain.

We neither asked nor answered the important question as to the nature of the relationship between auditory and visual attention. Anecdotal evidence suggests that the two

phenomena might be orthogonal; musicians often play with their eyes closed when performing improvised or experimental music (as did QB when playing *Occam Delta XV*), but it cannot be concluded that they are not listening to each other when they do so. It might be, however, that visual attention primes auditory attention, so that musicians listen to what they are looking at. Thus closing one's eyes while playing may be a strategy for preventing irrelevant visual from interfering with auditory attention.

The findings of our study suggest that it would be worth exploring the role of listening in musical practices that produces trance-like experiences (Rouget, 1985) or levels of absorption (Høffding, 2019) resulting in a loss of the sense of self. In our analysis of participants' listening orientations over the course of the performance we observed some surges in self-oriented listening at moments of greater timbral complexity when it was more difficult to perceive who was playing what. For example, SB appeared to ground herself in the middle section of the work by changing her focus of attention to self-oriented listening. This suggests that total absorption in the collective sonic texture (or being "in the zone," as the participants put it) was not entirely desirable, at least in this performance. This finding is in line with those of studies showing that the ability to distinguish one's own actions from those of co-agents facilitates interpersonal coordination (Liebermann-Jordanidis et al., 2021). Even in the music of Radigue, the participants still aimed to separate themselves from each other. This issue too could be studied in future using a wider range of minimalist or repetitive musical contexts from which a strong sense of we-agency is likely to emerge, given that in such contexts it is hard to perceptually discriminate the contributions of each agent (Pacherie, 2014).

Despite the advantages of our methods for the analyses we have reported, our study suffers from two important limitations. First, we collected data in the intimate space of a recording studio, with the performers very close to one another. This might favor certain listening behaviors, with a greater focus on peri-personal space. From this perspective, it would be interesting to replicate the study using a live performance of *Occam Delta XV* to determine the effects of the concert space and presence of an audience on participants' listening strategies. Second, we asked participants to provide annotations representing a record of their auditory attention, as they recalled it after the performance. Our protocol did not allow us to decide whether they had chosen to focus their attention on a particular player

or event or if their attention was drawn by a salient sonic property of the collective performance. Also, we operationalized auditory attention somewhat crudely in our interface by forcing participants to choose between one of options (oneself; one of the other three participants; the group), rather than indicating precisely what they were listening to. For these reasons, it would be valuable in future research to adopt a mixed-methods approach, using the videos and graphs produced by the annotation interface as interview prompts to gather richer and more nuanced verbal data reflecting the participants' listening behaviors.

While the music of Radigue has long been marginalized, it has now gained worldwide recognition. It is perhaps successful because of the challenges that the musicians who perform it have to face, and the singular sound world they create when they overcome these challenges.⁶ Our study represents a first attempt to identify some of the attentional processes that make it possible to perform this music. Further empirical work is needed to paint a more complete picture of the performance practices associated with it and, more generally, other experimental music that shares its important aesthetic traits. We believe that our approach has considerable potential for renewing the theoretical and methodological paradigms for studying joint music-making, and hope to have paved the way for important future research. The intricacy of the listening strategies that emerged during the encounter between QB and the music of Radigue —albeit in one performance only—points to the acute, active, and challenging nature of auditory attention when performing such introspective pieces, and has the potential to inspire further explorations of virtuoso listening during the course of joint musical activity.

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⁶ For example, it is the potential of risk embedded in Radigue's music and collaborative practice that initially attracted QB to Radigue's music (Reference anonymized). Indeed, her musical material and her method of transmitting it orally creates a space where hyper-control and traditional virtuosity need to give way to risk. In addition to experiencing a loss of self when performing Radigue's music, QB must neither over-control nor force it. If they do, the fragile microbeats forming her signature style cannot emerge, and neither will the music.

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