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Current Technologies and Compositional Practices for Spatialization: A Qualitative and Quantitative Analysis

Spatialization, the synthesis of spaces and spatial properties of sounds for a listener, is a growing field of interest for researchers, sound engineers, composers, and audiophiles. Due to broad and diverse viewpoints and requirements, the understanding and application of spatial sound is developing in many ways. To benefit from varying viewpoints, individuals involved in artistic practice and those involved in theoretical or applied research need to engage in regular dialogue. Blesser and Salter (2006, p. 184) reported on the long-term relationship between artists and audio researchers regarding virtual spaces, which is "the story of an evolving relationship between sophisticated audio engineers, creating tools, and impatient artists, incorporating such tools long before they are fully defined." Otondo (2008) showed that over the last ten years the technical equipment of composers has improved both in quality and quantity, with sound spatialization based on five or more loudspeaker channels being increasingly preferred over traditional two-channel stereo systems. Novel spatialization tools, however, have hardly found their way out of the research lab: Artists continue to use conventional and familiar spatialization techniques. As composer Natasha Barrett said, "the spatialization equipment and technology have become readily available, but the users haven't caught up" (Otondo 2007, p. 17). To effectively guide future research efforts, we need to understand this lack of coherence between development and creative musical application.

Computer Music Journal, 35:1, pp. 10–27, Spring 2011

Methodology

In our study, a Web-based questionnaire was designed and presented to composers and sonic artists to help understand how they use spatialization, what spatial aspects are essential, and what functionalities spatial audio systems should strive to include or improve. Additionally, we surveyed the degree to which artists know, and have already applied, recent developments in spatial audio technologies.

The survey, consisting of multiple-choice and comment-form (open-ended) questions in English, was divided into two parts: 13 compositional and 11 technical questions. Unlike the multiple-choice questions, answering the open-ended questions was not obligatory. Each multiple-choice question included a comment text field to account for individual responses, and the arrangement of multiple-choice responses was randomized across respondents to reduce order effects. To ease the response-entry process for the respondents, this survey was deployed over the Internet and could be stopped and continued at any time. Open-ended questions were independently analyzed by two researchers to control for biases in interpretation.

Respondents

The survey was announced in March 2008 on several appropriate Web domains, such as SpACE-Net, and mailing lists by the Canadian Electroacoustic Community (CEC), the British Sonic Arts Network (SAN), the Australasian Computer Music

Figure 1. Geographic distribution of the 52 respondents.

Association (ACMA), and Norwegian young composers. Further, several invitations were directed to specific contemporary composers, including the panelists of the 2008 CIRMMT/UCSD Music + Technology Incubator III workshop. Responses were collected for 14 days and 52 surveys were completed (approximately 55 percent of all the surveys that were started). This response rate can be considered as very high for a non-reward, Web-based survey, and suggests demand and interest.

Respondents were primarily male (85 percent) and predominantly from Europe and North America (see Figure 1). For musical education, more than 80 different universities/conservatories were named, of which the most frequent were Université de Montréal (17 percent), University of Birmingham (10 percent), and Stanford University (8 percent); several respondents were self-taught (11 percent). Respondents reported an overall composition experience of 20 years on average, 14 years of which was computer-aided, and 10 years of which involved spatialization. Remarkably, several experienced composers reported a longer history of using spatialization than applying computer techniques to their work. Because we expected that work experience might affect responses, composers were separated into analytic groups according to their reported experience in using spatialization techniques: "beginners" (under 5 years), "intermediate" (5–10 years), and "advanced" (more than 10 years), resulting in equal-sized groups.

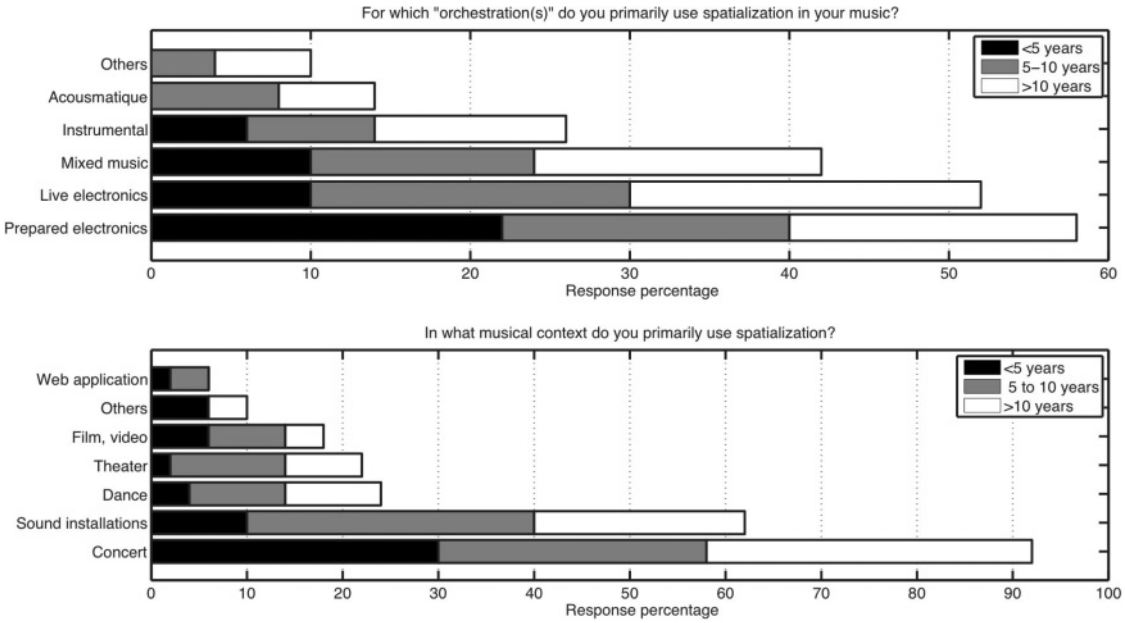
Responses

This section presents and interprets the participants' responses to questions regarding compositional aspects, the working environment, and the usage of spatialization tools.

Fields and Forms of Application

To create valid use cases in research and development, we asked respondents to specify the artistic fields and presentation forms in which they apply spatialization. The upper part of Figure 2 shows that more than half of the respondents use spatialization for live electronics and/or for prepared electronics (fixed media). The "Acousmatique" classification was added here because several composers explicitly indicated this category in the comment text field. Although prepared electronics seem to be equally distributed among experience groups, one can see

Figure 2. Distribution of "orchestration" and contexts in which spatialization is used as a function of compositional experience. Multiple categories could be selected. (In this and similar figures, the rightmost edge of an entire bar measures the total response percentage across all three experience groups. Within a bar, the response percentage for a given experience group is given by the width of the corresponding colored section of the bar, not by the absolute position of that section's rightmost edge.)



that in live electronics, spatialization is used less by "beginners." One could speculate that a live electronics project might generally be a bigger challenge for an artist than a fixed-media production, such that "beginners" are likely to reduce a project's complexity by avoiding spatialization. Similarly, on average we find fewer "beginners" in the mixed-music category (electronics combined with instrumentalists). An Analysis of Variance (ANOVA) revealed that the number of orchestrations per respondent increases significantly across experience groups ($F(2, 46) = 5.6$, $p < 0.007$).

More than 90 percent of the respondents present spatial music in a concert situation (see lower section of Figure 2). The second most frequent presentation form is sound installations (more than 60 percent). New media forms, represented through the categories "Web application" and "Film, video" are the least common forms for respondents with more than 10 years of experience.

Compositional Motivation and Realization

In an open-comment form, we asked composers why they use spatial aspects in music. The comments were sorted and clustered into response categories (see Table 1).

Table 1. Why Composers Use Spatial Aspects in Their Music

Category	*Total Responses*	*%*
To enhance the listening experience	29	58
As a paradigm for artistic expression	22	44
To organize and structure sounds	20	40
To experiment with technology and spatial effects	12	24
Perceptual motivation	12	24
Segregation and blending of sounds	11	22
To add motion and dynamism	9	18
To make sounds more natural and vivid	7	14

Fifty responses in open-comment form. Respondents chose multiple categories.

Most frequently (58 percent), composers intentionally use spatialization to enhance the listening experience. Multiple responses suggest that such an augmented experience is often achieved through immersing the listener in sound. Spatial aspects heighten the experience of space and time and

therefore "intensify the sensory experience for the listener" per a British composition student. Several artists believe that listeners find it more interesting to hear sounds coming from a variety of directions than from only the traditional frontal stage direction. For almost half (44 percent) of the respondents, spatialization is a compositional paradigm. "There is no other way to express the ideas I am working with," said a 39-year-old artist who works on spatial sound installations, Internet applications, and concert music. Another composer working on prepared electronics for sound installations and film/video said that spatialization is "a subtle but important part of the whole in [his] compositions." More precisely, a composer who works with Wave Field Synthesis (WFS) said that he is not interested in the accuracy of movement and localization of WFS, but in the way an individual sound can create a space itself without changing acoustical properties of the room, e.g., by using additional reverb. Forty percent mentioned that spatial aspects help to organize and structure music. "The spatial structure of a work may be of equal importance as its organization in terms of pitch, timbre or rhythm," stated a composer who primarily presents fixed-media pieces within a concert situation. Another mentioned that spatialization "adds one or more artistic layers to a piece."

A quarter of the responses (24 percent) indicate that many composers are attracted to the experimental and exploratory side of spatial effects and spatial sound technology. One composer reported that in spatialization "there is still lots of room for innovation, which I like." Another composer working in the field of live electronics said that spatial parameters are available *a priori* in the world of computer music and therefore have to be at least considered. Experienced composers are also attracted by the novel possibilities spatialization offers. "Spatialization gives the composer the means to expand their gestural palette into the spatial domain in a dynamic way not previously possible." Nearly a quarter (24 percent) of the respondents replied that spatial aspects are perceptual attributes of hearing sounds and music. "Life is spatial, music is spatial"—therefore those attributes should be addressed in music. Composers also explicitly identified the use of sound segregation and sound blending, key concepts of auditory scene analysis research (Bregman 1990; Harley 1998), as a motivation for spatialization (22 percent). A composer working for more than 5 years with spatialization said he can "present more sound material at the same time without losing . . . clarity," while others feel that "complex music becomes more comprehensible." Respondents also mentioned that spatialization is applied to add motion and dynamism (18 percent) or to make electroacoustic sounds more real and vivid (14 percent), "to give sounds an identity."

Very often, composers simultaneously addressed several of these response categories. For a more comprehensive understanding, we studied these intercategorical relations and found a strong connection between the three categories "To enhance the listening experience," "As a paradigm for artistic expression," and "To organize and structure sounds." Many responses that addressed "To experiment with technology and spatial effects" also relate to these three response categories and indicate how strongly experimentation permeates current spatial music. Furthermore, "Segregation and blending of sounds" is strongly connected with "To organize and structure sounds" and "To enhance the listening experience." Sound segregation is known to facilitate a listener's processing of compositional structure.

Continuing the previous question, we asked how composers configure sound elements to realize spatialized sound experience. If developers knew more about such methods, development could be better applied and could, for instance, increase the usability of spatialization tools. This question triggered a variety of unique responses that are related to musical context and site-specific aspects, and are therefore hardly generalizable. The responses (see Table 2) mainly addressed methods for moving sound sources and their distribution in space, and could involve experimentation with the sound material and the acoustics of the listening room. Often these methods are used to achieve a contrasting perception of sounds (i.e., clarity vs. blurriness, close vs. far, reality vs. surreality, thick sounds vs. thin sounds, dense vs. open).

Table 2. How Do You Configure Sound Elements to Achieve Spatialized Sound Experience?

Category	*Example*
Distribution and position	Distance and depth Algorithmically generated distributions Spatial organization according to timbre, texture, and musical function Spatial granularization Stereo tracks as source material Diffuse sounds (multi-speaker distribution) Mono sound reproduced from one or two adjacent loudspeakers Size of the spatial image Planes, subspaces and hierarchical sound layers Front (stage) is the focal point
Movements	Slight movements Contrast static vs. dynamic Many movements with a small number of sounds Strength of movements according to musical function: melody moves more than other sounds Prepared trajectories Instrumentalists move during composition Live performers moving loudspeakers
Others	Changing loudness and dynamics Spectral filtering Reverberation Simulating room acoustics Surreal spatial impressions

Forty-seven responses in open-comment form.

Working Environments

In the Composition Studio

Figure 3 shows how often various reproduction systems are used in a composition studio. Possible responses were limited to a list of reproduction setups according to the frequency categories: "never," "seldom/sometimes," "usually," and "always." As the main reproduction system in a composition studio, 35 percent of the composers "always" use a two-channel stereo loudspeaker setup and 20 percent "always" use headphones. Multi-loudspeaker arrangements, such as quadraphonic or 5.1, are generally used only "sometimes" or "seldom." More than 50 percent of the composers "never" use, or do not have access to, seven- or eight-loudspeaker configurations. Because stereo and headphone reproduction is so common in the compositional phase, one might speculate whether, instead of using expensive multi-loudspeaker setups, composers use binaural or transaural processes to spatialize audio around their head with only two audio channels while composing. Composers' responses to a question concerning whether binaural or transaural versions of their spatial music have been released suggest that these techniques are rarely used.

At the Venue

Most composers (76 percent) consider the loudspeaker arrangement in the performance situation as different from their studio environment. Very often, a venue is equipped with more loudspeakers than the composer's studio. An acousmatique composer said "I have eight loudspeakers in my studio, but most of my work is intended for sixteen loudspeakers, and more recently, for twenty-four speakers. The eight loudspeakers in my studio give me an idea." Another said that he works in a variety of composition studios with two to five loudspeakers, whereas he performs in venues with more than 50 loudspeakers. In contrast to reproduction systems found in composition studios, an eight-loudspeaker array is presently the most common loudspeaker configuration in venues and electroacoustic music festivals (Lyon 2008). However, loudspeaker setups also differ in terms of sound quality and in the horizontal and vertical distance between a listener and the loudspeakers. Several composers mentioned that their studio is acoustically treated to minimize the effect of room reflections, in contrast to the performance venue, where reverberation can be expected. The most common venues are traditional concert halls, specialized venues for electroacoustic music, and gallery spaces (see Figure 4). It is surprising that cinemas are not generally used, as they provide standardized (e.g., the THX standard) acoustic treatment and multichannel loudspeaker systems. On average, composers work in approximately four

Figure 3. For composing spatialized music in your studio, how often do you use the listed reproduction systems?

Figure 4. In what kind of venues are your spatial compositions performed? Others = bars and clubs, classrooms, spatial audio labs, virtual reality caves, spaces with remarkable acoustics.

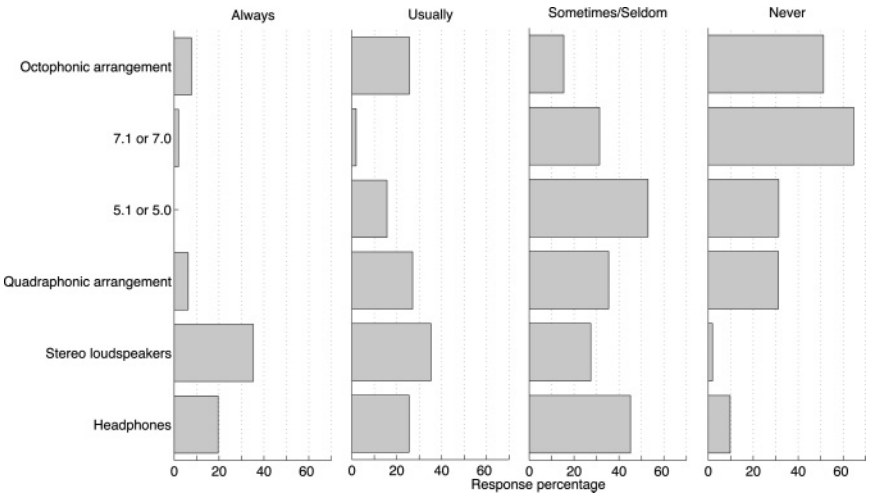


Figure 3.

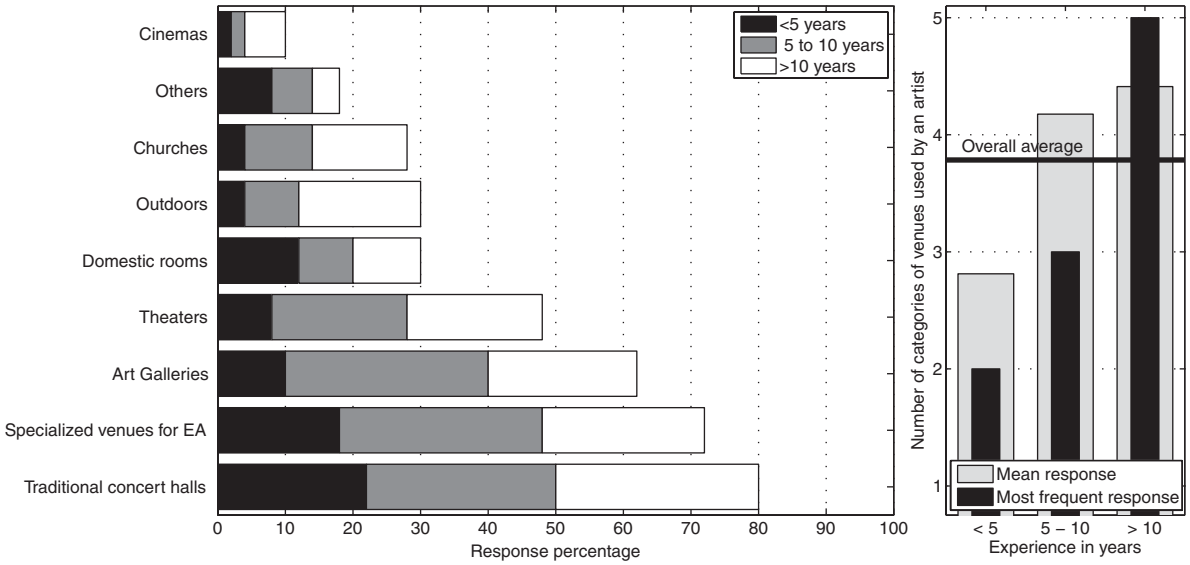


Figure 4.

different kinds of venues; this number increases with more experience (see Figure 4, right).

Artists were also asked about the main challenges venues posed to their compositional aspirations (see Table 3). The main challenges are related to the acoustic conditions, to technical limitations of the venue, and to time constraints within the venue. For the acoustical conditions, challenging attributes of venues are room dimensions, raked seats (i.e., an inclined floor), modes and resonances, and too much reverberation, which dominates the perception of spatial elements in a composition and causes microphone feedback for live electronics. The "sonic leakage" from one exhibition to another is an additional problem for sound installations. Regarding the technical limitations, the main complaint

Table 3. What Are the Main Challenges of Venues You Have Faced so Far with Respect to Your Compositional Aspirations?

Category	*Total Responses*	*%*
Acoustical conditions	20	48
Technical limitations of the venue	16	38
Time constraints	13	31
Non-ideal loudspeaker and audience location	13	31
Staff and audience	8	19
Sweet spot	7	17
Cost of production	2	5
No problems	3	7

Forty-two responses in open-comment form.

was the limited number and quality of loudspeakers. Nearly one response out of three reported that the time allocated for arranging and optimizing the loudspeaker configuration at the venue is too short. Further, non-ideal locations of loudspeakers with respect to the audience and a small listening area (sweet spot) were reported. Many venues have room dimensions that complicate the setup of equidistant loudspeakers, as required by most spatial rendering algorithms. Composers who work with elevation and height face the difficulty that loudspeakers are often configured in a horizontal-only arrangement; hanging loudspeakers is almost always impossible in traditional concert spaces and opera theaters. It was reported that venue managers, without the agreement of the composer, repositioned the seats of the audience or placed extra furniture in the venue. This resulted in seats being too close to loudspeakers and walls, degrading the sound quality for listeners. Sometimes an ideal placement of loudspeakers may not be possible due to aesthetic constraints of the stage or lighting designer.

Because of the diverse reproduction conditions across venues, artists have developed (compositional) strategies to adapt their work. "I tend to accept the effect of venue as part of the concretization of my ideas," said an artist who performs in traditional concert halls, specialized venues for electroacoustic music, and art galleries. Other composers reduce their technical requirements from the beginning, thereby limiting the spatial possibilities. "As I have moved more towards visual arts, I have discovered that even getting adequate stereo playback in a venue is problematic. I certainly don't try for anything beyond 5.1," explains an Australian artist. Some responses suggest that composers tend to work with more extreme and obvious spatial properties, such as heavy panning rather than using more subtle spatialization techniques, to ensure that at least these gestures will be perceived. Composers of fixed-media pieces create different versions to account for different loudspeaker arrangements. If there are more loudspeakers than tracks, some tracks may be assigned to more than one loudspeaker. Therefore, "the more the number of tracks, the less the adaptability" according to one artist. "In the studio, I usually use a stereo system. At the performance place, I then adapt my work to the diffusion system," added a Canadian composer. An Austrian composer simulates "real-world condition[s]" by using outdoor loudspeakers in his studio when he works on outdoor installations.

Preservation of Spatial Music

The preservation of electroacoustic music is an increasingly important topic and is especially challenging when spatialization is involved. Thus, this questionnaire addressed media formats and notation practices.

Media Formats

One multiple-choice question asked what media formats are used for publishing spatial music. The two-channel audio CD is the most common medium (80 percent), and all other formats are used by less than 40 percent of the respondents. Interestingly, the average respondent uses DVD, currently the most common medium for multichannel audio work, as often as conventional two-channel MP3. It should be mentioned that in a sound installation project, for instance, a two-channel recording is often made mainly to serve as documentation. One composer mentioned that he will use the "good old audio CD" until there is a proper storage standard for multichannel files. Spatial music is also often stored on

data DVDs that contain either (1) PCM audio files for each individual loudspeaker feed (fixed media) or (2) the composition within the audio software project files. An acousmatique composer, one of the 10 percent who do not use any media, stated, "Publication is not important for me, I mostly work for live performance." The level of experience does play a role in choice. Only those in the "beginners" group were found to use MP3-surround, a technology to encode spatial audio in a conventional MP3 file. Another respondent anticipates that fixed media will fade away in a few years in favor of sound files on generic media that can be adapted for different listening scenarios.

Notation

Through scores, compositions can be stored, exchanged, studied, and performed, but also revised and adapted after their initial creation. To the authors' knowledge, there is no common notation format or standardized vocabulary to describe spatial parameters (see Kendall and Ardila 2008; Kendall, Peters, and Geier 2008). Therefore, it seems reasonable that 62 percent of the respondents do not use notation for spatial aspects. Most composers argued that for (fixed) tape music, there is no need for a score, or they haven't found a satisfying way to notate spatialization. Others said that there is no score because spatialization is created through improvisation and experimentation or generated by real-time algorithms. Composers seem to have developed individual spatial notations, ranging from photos and drawings over diffusion guides, to poems and descriptive text, to sonograms of the music with annotations. Notation forms also depend on the production environment. When working in media programming environments such as Max/MSP or SuperCollider, spatial parameters are stored in data arrays within the composition patch, in contrast to digital audio workstations (DAWs), where built-in track automation is used to store and recall parameter changes. "When working with the WFS system, the drawings become one of the main parts" was a response that suggests that the notation scheme and the technical environment, including rendering concept, can influence each other.

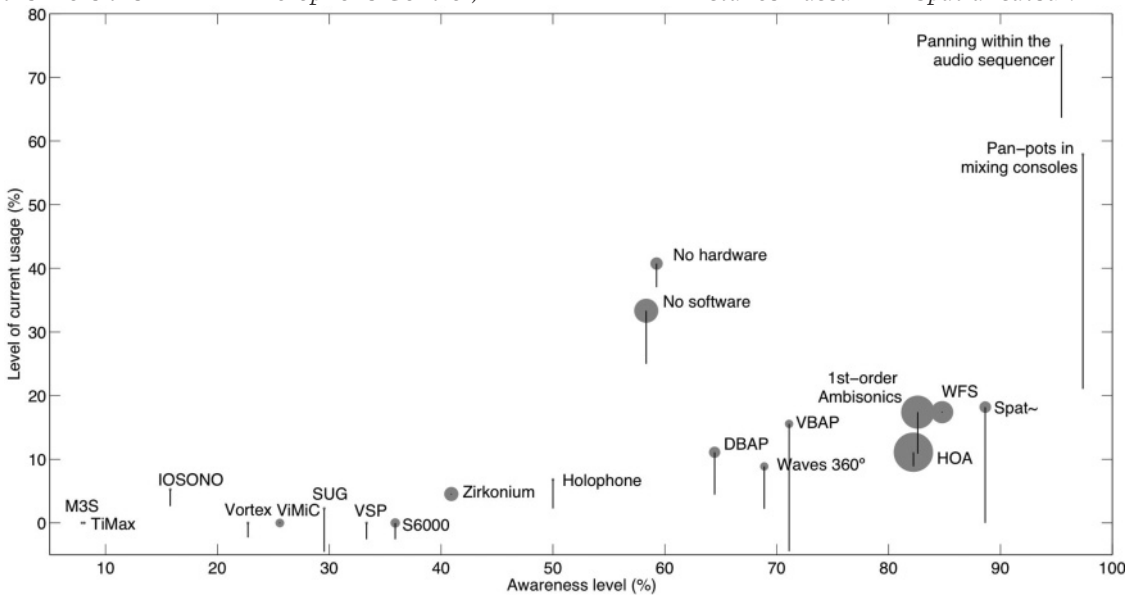
Artists and Their Spatialization Tools

We are interested in what composers think about the software and hardware tools they use for spatialization, and how their feedback can affect future development. We are also interested in the degree to which composers are aware of recent developments in spatial audio technologies. Figure 5 shows the responses to the question "What software and hardware tools have you used for spatial compositions?" according to the categories: Never heard, Heard about but never used, No longer in use, Currently in use, and Planning to try it. The list of spatialization tools, which the authors assembled by reviewing spatialization applications, is a mix of concepts and products. The experimental approach to spatialization (Table 1) is supported in the choice of tools: 20 percent of all respondents use self-made or custom-made tools and 31 percent use a media programming environment such as Max/MSP or SuperCollider. The primary spatialization tools are the built-in panning devices of DAWs and audio sequencers (75 percent) and panning performed with a hardware mixing console (58 percent). It seems that older technologies, such as the panning potentiometers (pan-pots) in mixing consoles, are well known, but many are no longer used (in case of pan-pots, 37 percent of the respondents no longer use hardware mixers). Similarly, IRCAM's Spatialisateur, under development since 1991 (Jot 1999), and VBAP (Pulkki 2001) from 1998 are widely known, but are also often replaced by other tools.

The categories "No hardware" (41 percent) and "No software" (33 percent) also account for composers who work with instrumentalists and without any electronics. It is surprising to see that several respondents are planning to work without software. Does that mean that they are frustrated with current spatialization tools? The categories "Panning with mixing console" (58 percent) and "No hardware used" (41 percent) form 99 percent of the responses, and artists show little awareness of other hardware-based spatialization tools.

According to Figure 5, the rendering concepts of first-order and higher-order Ambisonics (HOA) seem to be the most interesting techniques for future compositions. However, people currently seem slightly

Figure 5. What software and hardware tools have you used for spatial compositions? The longer the vertical line under the bubble, the less the composer continues to use this tool. The bigger the bubble, the more the composer plans to try it. M3S = Sonic Emotion M3S WFS system; TiMax = TiMax Audio Imagine System; IOSONO = IOSONO WFS system; Vortex = Vortex Surround tools; ViMiC = Virtual Microphone Control; SUG = Space Unit Generator; VSP = Virtual Surround Panning in Studer-digital mixer; S6000 = TC-Electronics S6000; Zirkonium = ZKM Zirkonium; Holophon = GMEM Holophon tools; DBAP = Distance Based Amplitude Panning; Waves 360° = Waves 360° Surround tools; VBAP = Vector Base Amplitude Panning; HOA = Higher Order Ambisonics; WFS = Wave Field Synthesis; Spat<= IRCAM Spatialisateur.



more aware of Wave Field Synthesis (Rabenstein, Spors, and Steffen 2004) than Ambisonics. Although HOA and WFS are both high-resolution spatial sound reproduction techniques that are conceptually based on the physical reconstitution of a wave field (Spors and Ahrens 2008), one wonders what makes HOA more attractive. Might it be Ambisonics' ability to store spatial audio material independently of the reproduction setup? Or, is it that by defining the "Ambisonics order" and choosing the number of loudspeakers, the size of the listening area can be scaled to different listening scenarios? WFS requires a large number of loudspeakers and their spacing creates perceivable artifacts throughout the listening area. By using a periphonic loudspeaker dome, Ambisonics can reproduce elevated sounds, which is an important feature for many composers (as will be seen later in Figure 7). To our knowledge this feature is not currently supported by available WFS systems. Moreover, WFS systems are still rare. Approximately 20 research labs and about 20 auditoriums are equipped with a permanent WFS system (De Vries 2009). Ambisonics systems may simply be more easily accessible to artists. There are several Ambisonics tools up to eleventh order that are freely available (e.g., Schacher 2010). Although these Ambisonics tools do not work in high enough Ambisonics orders as to compete with WFS's sound reproduction abilities, composers can adapt to the Ambisonics concept by using lower-order forms in production studios and for concert performances (Färber and Kocher 2010) and can more easily switch to higher-order systems in the future. However, the small number of loudspeakers that are currently used in composers' studios (Figure 3) suggests that more loudspeakers are required for these new spatial rendering concepts (e.g., WFS and HOA) to be applied. Despite the greater interest in HOA, WFS offers many compositional possibilities (see Baalman 2007). In contrast to HOA, if an artist only wants to present sounds from one side (e.g., from the front), loudspeakers do not have to surround the audience—an economic, aesthetic, and pragmatic argument. A composer working mainly with WFS systems reported that "the most interesting aspect is not the accurate movement of sounds nor their localization, but the way that an individual sound can create a space itself."

Besides these concepts and products, the survey revealed that many tools are unknown to the majority of artists. Are most users satisfied enough with their current choice of tools and not looking for

Table 4. What Is Your Motivation for Working with Your Current Spatialization Equipment (versus Using Other Tools)?

Motivation	*Total Responses*	*%*
Usability, learning curve	20	48
Quality of spatialization, fit to aesthetic goals	15	36
Availability, accessibility, and cost	15	36
Flexibility, versatility	12	29
Integration into existing technical framework	7	17
Reliability	6	12
Other	2	5

Forty-two responses in open-comment form.

other (perhaps more suitable) tools? Do composers rely mainly on audio sequencer software with integrated common spatialization features?

Choice of Tools

A composer's rationale for choosing his or her current spatialization tools provides insight into those choices. The responses, in comment form, are analyzed and grouped together in Table 4. Almost half of the responses are related to the usability of tools. Common replies include "simple," "intuitive," and "easy to use." Also, the challenge of learning how to use a tool is included in this category. Sixty-one percent of respondents think the time spent with spatialization tools could be reduced with optimization. The importance of time and usability are likely connected to the pressure composers feel to meet commission deadlines and to maximize work and creative outcomes within limited studio time and resources. People who invest time in creating their own spatialization tools reported that self-written software enables a personal approach to spatialization. Further, the user has control over all the essential parameters, suggesting that ready-made tools might be lacking in this respect. Half of the respondents use fewer features than their spatialization tools offer. Thirty-six percent of respondents base their choice of tools on the degree to which a specific tool can be applied in achieving compositional and aesthetic goals.

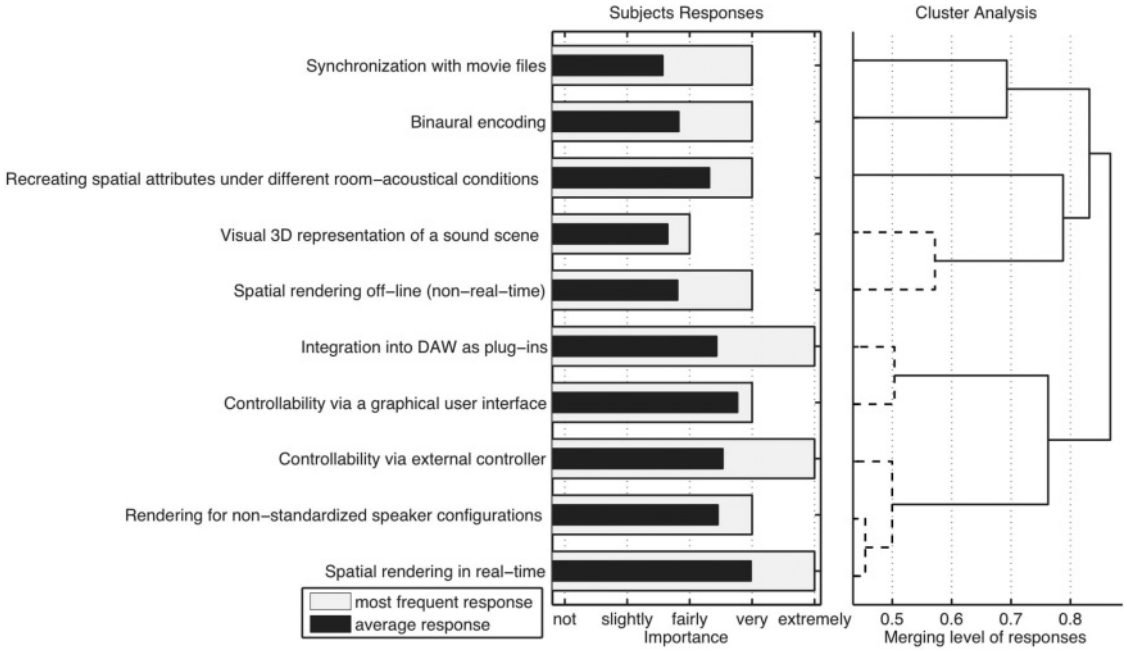
Responses to another question revealed that 30 percent of the artists are constrained by the number of sound sources that can be spatialized using their current palette of tools. Besides trying less limiting and more appropriate tools, faster and multiple CPUs will also help these composers. Flexibility and versatility were mentioned in 29 percent of the responses, whereas only 12 percent addressed the reliability of their tools. As reliability seems fundamental, we expected more responses for this aspect.

Importance of Technical Features

We asked respondents to rate the relative importance of ten technical features for their work using five categories: "Not" important, "Slightly," "Fairly," "Very," and "Extremely" important. The ratings result in relatively little variance; all technical features having an average around "fairly" important (see Figure 6, left). The feature "Spatial rendering in real-time" received the highest ratings ("very" important), whereas "Visual 3D representation of a sound scene" was rated lowest (less than "fairly" important). The most frequent responses demonstrate that there are three features rated as "extremely" important: "Integration into digital audio workstations as plug-ins," "Controllability via external controller," and "Spatial rendering in real-time." To the provided feature list, respondents added properties such as "Level visualization of each speaker feed," "Up- or down-mixing to eight output channels," "Managing trajectories, patterns, and direct control protocols within a database," and "Adaptation to different loudspeaker configurations."

Some of the technical features correlate moderately with each other (Spearman correlation $\rho(52) \approx 0.5$). A cluster analysis was performed on the individual responses in order to group technical features together that were similarly rated (see Figure 6, right). This cluster analysis suggests technical features that developers might want to conjointly address for different use cases (indicated with dashed lines in the figure). For instance, a spatialization tool that can be integrated as a plug-in into DAWs should

Figure 6. Rate the importance you attach to the listed technical features.

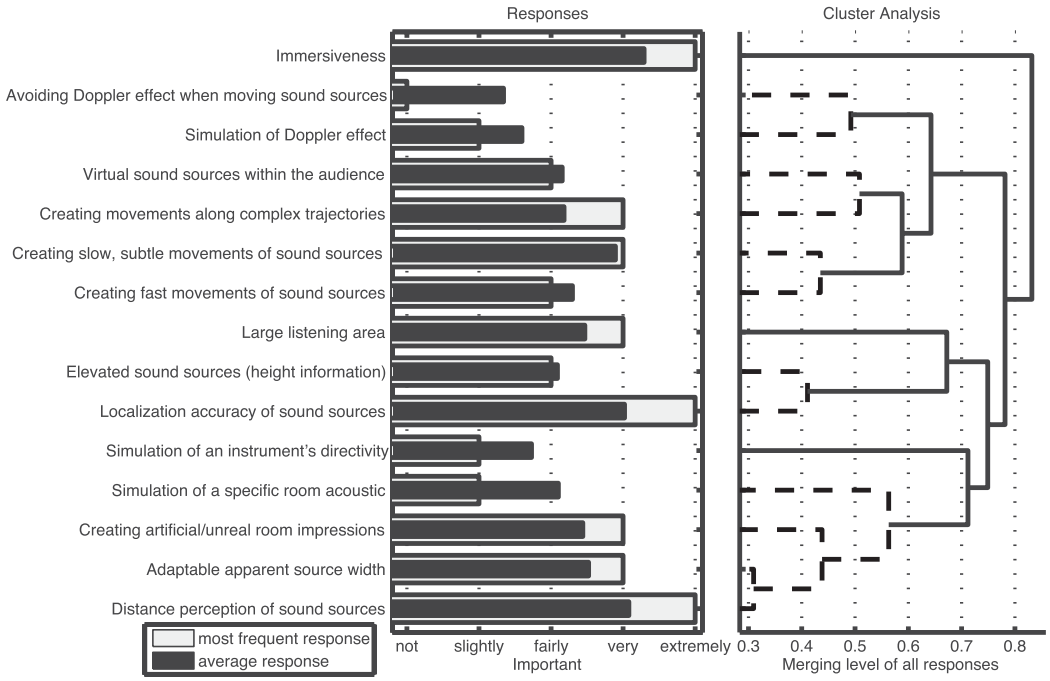


be equipped with a graphical user interface, whereas an application that renders a spatial scene in an audio-file in non-realtime should be equipped with a visual representation of the sound scene. Another grouping of features addresses real-time rendering in combination with external controllers and the rendering of non-standardized speaker configurations. The advantage of real-time rendering is that spatial parameters can be manipulated, e.g., via a gestural controller in real-time (Marshall et al. 2006). Furthermore, the rendering process can be adapted to accommodate a given loudspeaker arrangement and certain acoustic conditions.

Desired Features

When asked if features were missing, 41 percent responded "Yes" and 20 percent said "No." Often an improvement in the usability of the spatialization tools was requested, such as "intuitive interfaces . . . to control spatialization processes from a high level" or "scalable interfaces that can go from 2 to 500 channels." Another respondent wished to draw trajectories for multiple sound sources in one scene editor, rather than having multiple trajectory editors, one for each audio track, in a DAW. Others addressed the bus architecture in the DAW application, which often limits the number of loudspeaker feeds: "I prefer to use commercial DAW software, . . . but find most of the available multi-speaker tools inflexible and too cinematic." Another composer said that DAWs are too inflexible for live work and non-standardized playback scenarios. He misses features that facilitate flexible routing and control of stereo planes to various speaker sets. Generally, a higher degree of flexibility was requested. One respondent said that each tool has strengths and weaknesses, and it is very difficult for him to imagine a tool that does everything perfectly. To benefit from the power of individual tools, he proposed a framework that interconnects them. This might appeal to another survey respondent who wants to map parameters of time, pitch, timbre, and space in his music "through expressive software tools." Others would like to have tools that help to adapt music to the varying acoustical and technical situations of the performance venues. Lastly, respondents expressed the desire to easily apply different interface devices for controlling spatialization, e.g., for drawing trajectories of sound sources. Besides using common

Figure 7. Rate the importance you attach to the listed spatial feature. (Features are listed in an order determined by the cluster analysis on the right side.)



human–computer interfaces, such as a joystick or keyboard, it was suggested to develop input devices that are tailored to the specific needs of controlling spatialization, for example, multi-touch interfaces to visualize and control multiple spatialization parameters simultaneously.

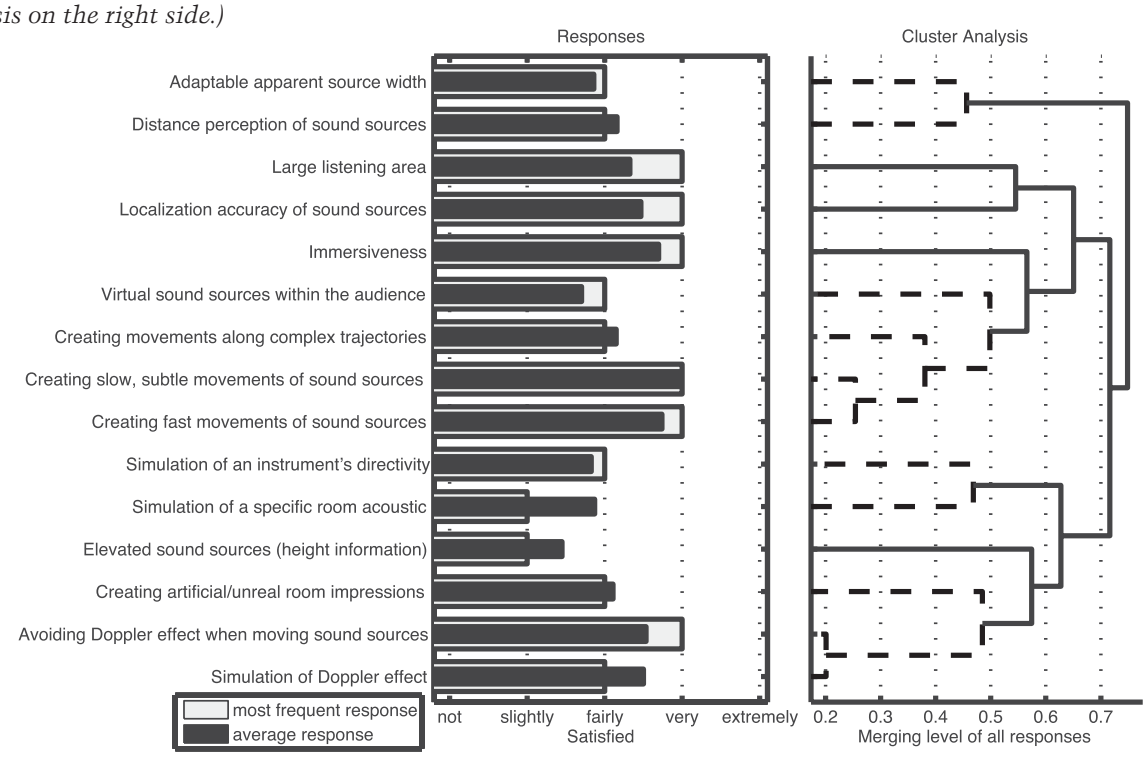
Analysis

In this section, we statistically analyze a subset of the responses to relate technical and compositional aspects to each other and to identify potential areas for further research and development.

Spatial Aspects: Compositional Importance and Their Fulfillment

We provided a list of 15 spatial aspects to discover which ones artists consider to be important, and to what degree they can be effectively created through their tools. First, the importance of spatial aspects was addressed and the responses were categorized as: "N/A," "Not," "Slightly," "Fairly," "Very," and "Extremely" important. The distribution of responses was: "N/A" 6 percent, "Not" 10 percent, "Slightly" 17 percent, "Fairly" 20 percent, "Very" 24 percent and "Extremely" 23 percent. Hence, almost half the ratings were extremely or very important (see Figure 7, left). Some composers mentioned that the degree of importance can change according to the compositional situation and the musical material. Other comments provided additional aspects not included in this question, such as "Spatial clarity and density," "Spatial perspective," and "Spatialization of timbre." The highest rated spatial aspects are "Immersiveness," "Distance perception of sound sources," and "Localization accuracy of sound sources." The aspect "Large listening area," a feature of the high-resolution reproduction techniques WFS and HOA, was rated as "very" to "fairly" important. The aspects of "Avoiding" or "Simulating a Doppler effect," a natural pitch change of fast-moving sounds, were surprisingly rated as least important. Considering that artists who were new to WFS reported disturbing sound coloration when moving sounds, one would have expected this feature to be rated with a higher importance. The higher ratings of

Figure 8. How satisfied are you with the ability of your preferred spatialization tools to produce the listed spatial aspects? (Features are listed in an order determined by the cluster analysis on the right side.)

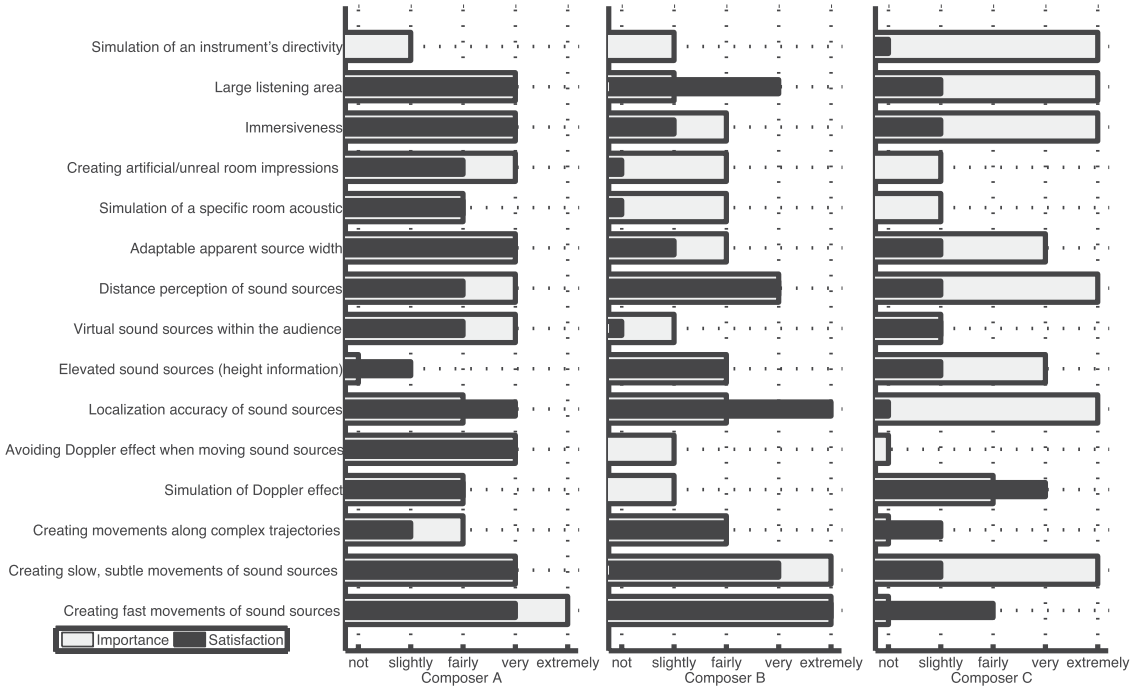


"Creating slow, subtle movements of sound sources" compared to "Creating fast movements" suggest that the unwanted Doppler effect might occur less due to the preference for slow movements, which minimize this percept. The aspect "Virtual sources within the audience" (also associated with WFS and HOA) was rated similarly to "Elevated sound sources" as "fairly" important.

The right panel of Figure 7 visualizes the cluster analysis according to a Spearman correlation between the features, computed from all individual responses. "Distance perception" of sound sources was very similarly rated to "Adaptable apparent source width" and also to the aspects concerning the creation of room impressions, e.g., through synthetic reflection patterns. Another interesting cluster was created from "Elevated sound sources" and "Localization accuracy," suggesting that composers favoring accurate localization are also interested in perceiving elevated sounds. Remarkably, "Immersiveness," the highest rated aspect, is unrelated in this analysis to any other presented aspect.

After rating the importance of spatial aspects, respondents were asked to rate in a similar way their satisfaction with the ability of their spatialization tools to (re)create those spatial aspects. The intention behind this question was to determine whether there is a gap between the creative desire and the ability to achieve compositional aims with available tools. The distribution of the responses among the satisfaction categories was "N/A" 18 percent, "Not" 8 percent, "Slightly" 14 percent, "Fairly" 23 percent, "Very" 27 percent, and "Extremely" satisfied 9 percent (see Figure 8, left). On average, 6 of the 15 listed spatial aspects that can be produced by the currently used tools were rated "very" satisfactory. Five aspects have mean ratings below "fairly" satisfactory: "Elevated sound sources," "Virtual sound sources within the audience," "Simulation of a specific room acoustic," "Simulation of an instrument's directivity," and "Adaptable apparent source width." As previously described, a cluster analysis was performed on the ratings. The resulting dendrogram (see Figure 8, right) shows similarities to the cluster

Figure 9. Spatial aspects, comparison of Importance and Satisfaction ratings from three different composers. Composer A: 1 year of experience; Composer B: 8 years of experience; Composer C: 30 years of experience.



analysis of the importance ratings (see Figure 7), that is, aspects regarding the Doppler effect and source movements were also found to be correlated.

Comparison

In comparing the average responses in Figure 7 with those in Figure 8, one sees that generally the satisfaction ratings are lower than the associated importance ratings. Figure 9 yields insight into the inter-individual differences by showing the ratings of three composers with different levels of spatialization experience. The slight tendency is that with more experience, the differences between importance and satisfaction ratings increase. "Nothing is perfect—dissatisfaction is a state of mind" commented composer C from Figure 9. In contrast, a generally satisfied artist with fewer years of experience than composer C said that he can usually get adequate results. His two most important spatial aspects are "Immersiveness" and "Creating slow subtle movements of sound sources."

Spatial aspects rated with the highest "Importance" but with low "Satisfaction" indicate a demand for better tools and, therefore, more research, innovation, and development. Table 5 shows the region of potential research and development interest (marked with "↯"). The responses are sorted according to this confusion matrix. For instance, composer A's rating of the "Large listening area" shown in Figure 9 fits into a +-region ("very" important and "very" satisfied), whereas composer C's rating would be sorted into a ↯-region ("very" important and "slightly" satisfied).

Table 5. Confusion Matrix Showing the Regions of Interest

		Satisfaction				
		Not	*Slightly*	*Fairly*	*Very*	*Extremely*
Importance	Not					
	Slightly					
	Fairly	↯				+
	Very	↯	↯		+	+
	Extremely	↯	↯	↯	+	+

"+" symbolizes cells with the best values in Importance and Satisfaction; "↯" symbolizes cells related to a low Satisfaction but high Importance.

Figure 10. Spatial aspects: All responses are sorted according to importance and satisfaction ratings. The bar height indicates the number of responses in a given category.

Figure 11. Spatial aspects: Top part of the plot shows items within the cells marked with a + according to Table 5, whereas the bottom part shows items within the cells marked with a ↯(y-axis = number of responses). The barplot also shows the responses according to the experience groups.

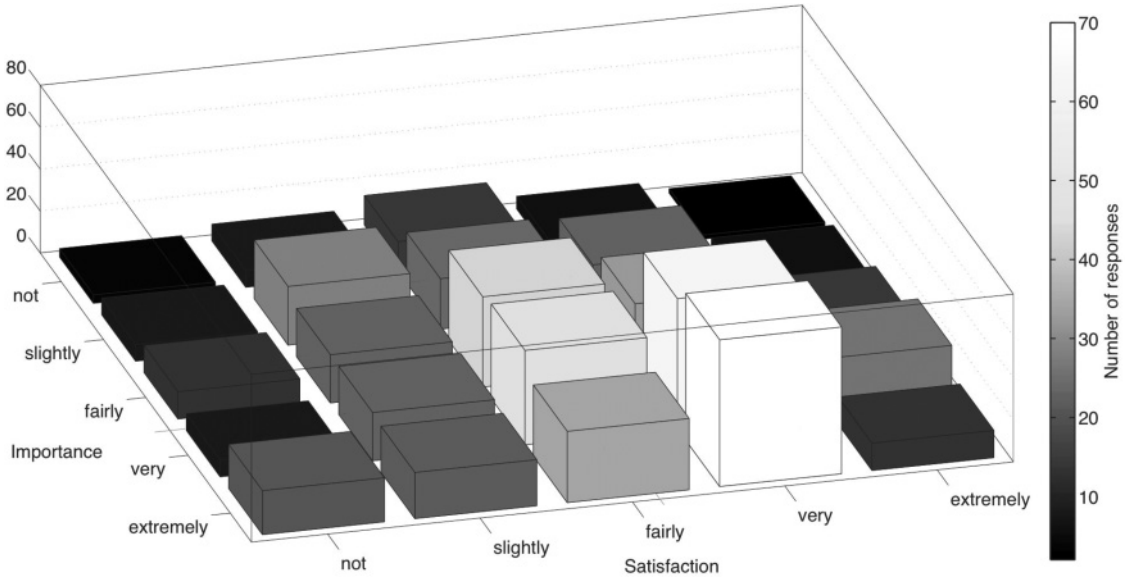


Figure 10.

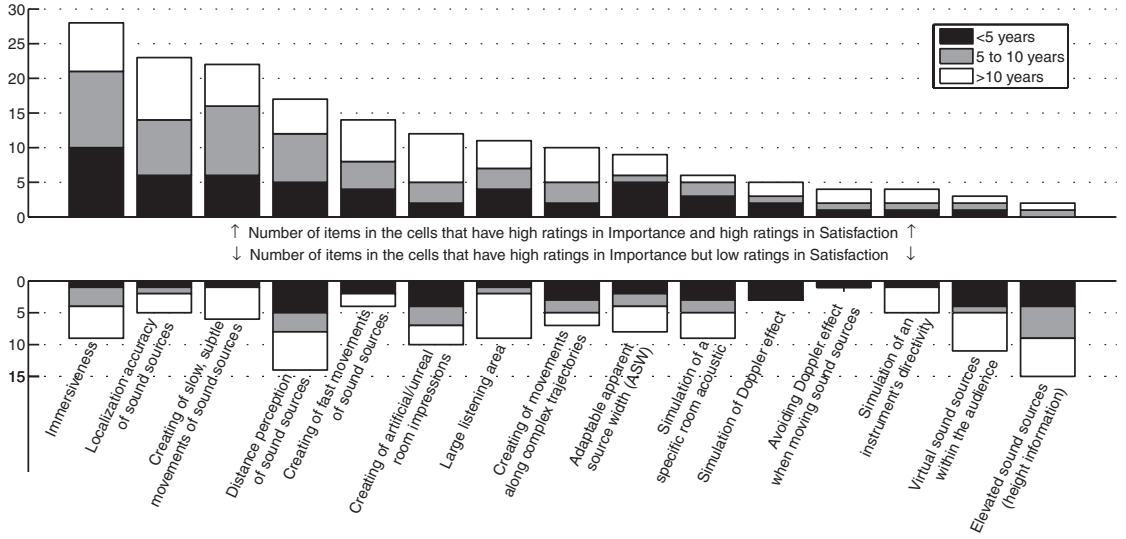


Figure 11.

The distribution of all responses can be seen in Figure 10. The higher the blocks, the higher the number of responses in this "Importance"/"Satisfaction" category. One can see that many ratings were given with the combination "extremely" important/"very" satisfied and "very" important/"very" satisfied (lower right corner). The middle-ground responses "fairly" important/"fairly" satisfied and "very" important/"fairly" satisfied were less frequent. The ↯-region in Table 5 represents more than 17 percent and +-region represents about 32 percent of all responses. An examination of these response regions according to the spatial aspects is shown in Figure 11. In the ↯-region (see Figure 11, bottom),

the aspects with the most responses are "Elevated sound sources," "Distance perception," and "Virtual sound sources within the audience." In the +-region (see Figure 11, top), the most frequent aspects are "Creating slow subtle movements of sound sources," "Localization accuracy of sound sources," and "Immersiveness." The latter two aspects were also judged with very high importance ratings (see Figure 7). Localization of sound sources is traditionally a strong field in psychoacoustics (e.g., Blauert 1997) and much research on spatial audio reproduction has evaluated this aspect (e.g., Pulkki and Hirvonen 2005). The analysis of the composers' responses suggests that research and development efforts have benefitted the field of musical applications. Interestingly, the aspects "Distance perception of sound sources" and "Creating unreal room responses" have relatively similar contributions in both regions, indicating a polarization of the responses. An analysis of these responses did not reveal the use of any particular spatialization tool as a potential explanation. However, the number of tools a respondent uses affects his or her satisfaction ratings; two or three tools are more satisfying than one, but six may not be.

Conclusion and Recommendations

The high response rate of this survey suggests that this kind of questionnaire is well received by artists. Researchers from related fields might be encouraged to similarly gather feedback from artists. The responses of 52 composers regarding technical and compositional aspects were analyzed to find general tendencies in current usage, while acknowledging the artistic individuality of each composer. Based on our interpretation of the survey findings, we derived the following recommendations for collaborative work between composers and researchers.

The technical and practical challenges of multichannel sound reproduction systems experienced by artists often relates to an under-utilization of available spatial features. To address these challenges, one has to acknowledge the higher technical complexity of multi-loudspeaker setups, especially the emerging high-quality spatialization techniques WFS and HOA, which require careful calibration of the equipment for full compositional advantage. To familiarize composers with new technology, the learning curve must be kept reasonably shallow (i.e., gradual). Good usability (e.g., avoiding cumbersome command line control) and the possibility of integrating new tools into common compositional environments are paramount and can lower the entry barriers for artists. Many DAWs (the most commonly used compositional environment, Figure 5) are limited to eight-channel spatialization. To accommodate the needs of high-quality spatial rendering concepts, the bus architecture must be extended to allow for massive output channels.

We also saw the demand for technology to give composers a feeling of the venue acoustics while working in the studio. Regarding new technologies, a number of responses suggest that some artists are motivated and technically experienced enough to explore the artistic potential of new or unreleased tools and become "early adopters." Real-world loudspeaker setups often differ from the standardized systems usually employed in listening experiments. More ecologically valid speaker configurations in the labs yield more meaningful data that better generalize to real-world conditions. The first part of the survey tells us where, why, and how spatial concepts are applied, and this information can be used by researchers and developers to create, in the labs, meaningful test environments that approximate real-world scenarios. Composers could support this effort by making parts of a composition accessible to researchers and by supporting the development of spatial-notation or description systems as proposed by Kendall, Peters, and Geier (2008). Apart from increasing the potential of preserving compositions, a common description format could let developers more authentically re-render spatial music and evaluate novel rendering methods or loudspeaker configurations. It is necessary to investigate how diffusion practice, as a prominent form of sound spatialization, can be incorporated into notation/description approaches.

In this article we have analyzed a survey of the compositional use of spatialization by composers.

The purpose of the survey was to give an overview of the current state of practice in order to guide future research and development of spatial audio systems.

Because the questionnaire was presented in English, we acknowledge that language barriers might have created a bias, leading to an underrepresentation of African, Asian, and South American artists (see Figure 1). However, because the respondents showed a great diversity in composing experience, age, and place of education and residence, we believe that the responses represent a meaningful cross-section of composers' views on compositional and technical aspects of spatialization. Besides the expected individual differences in composers' responses, we also extracted common themes in motivation, compositional practice, preferences, and critiques of available audio technologies. We hope that our findings will help enable communication between artists and researchers in order to refine future spatial audio technologies that will enhance future artistic practice. As a side note, although the survey took place in 2008, the data are still relevant: composers have directly addressed how time-consuming it is to change from one tool to another. Besides mentioning steep learning curves, they clearly operate on tight deadlines, which leaves little time for exploring alternative and novel technologies. However, the interest in tools that fit their needs is high.

Acknowledgments

This work was funded by a grant from the Canadian Natural Sciences and Engineering Research Council (NSERC) and the Canada Council for the Arts (CCA) to Stephen McAdams; and by the Centre for Interdisciplinary Research in Music, Media, and Technology (CIRMMT). Thanks to Matthias Geier, Sandra Duric, Finn Upham, and Catherine Guastavino for discussions and suggestions during the different phases of this research.

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