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Perception of Spatial Sound Phenomena Created by the Icosahedral Loudspeaker

Abstract: The icosahedral loudspeaker (IKO) is able to project strongly focused sound beams into arbitrary directions. Incorporating artistic experience and psychoacoustic research, this article presents three listening experiments that provide evidence for a common, intersubjective perception of spatial sonic phenomena created by the IKO. The experiments are designed on the basis of a hierarchical model of spatiosonic phenomena that exhibit increasing complexity, ranging from a single static sonic object to combinations of multiple, partly moving objects. The results are promising and explore new compositional perspectives in spatial computer music.

The icosahedral loudspeaker (IKO, cf. Figure 1) is a compact, 20-sided, 20-channel playback device that uses acoustic algorithms to steer sound into freely adjustable directions. These acoustic beams (referred to in this article as *sound beams*) are not only freely adjustable in terms of their radiation direction and beam width, it is also possible to blend multiple beams. A metaphorical idea behind using these beams in music is to "orchestrate" reflecting surfaces, yielding useful effects in the perceived spatial impression.

The particular perception of the IKO's effects depends on the sonic material, how sound beams are configured and mixed, and on the room situation.

Over the last six years, two basic staging constellations of the IKO have been shown to be feasible from an artistic point of view: those in typical rectangular rooms and those that utilize a concave setup of reflectors behind the IKO. Staging directly affects the sound-propagation paths in concert situations and, thus, the number of discretely localizable directions.

In rectangular staging situations, the IKO is placed near the corners of the room, allowing the orchestration of at least two side walls (see Figure 2a). For situations that are more complex, a concave set of reflectors are placed behind the IKO. This permits more flexibility in setting the number of reflections, as in Figure 2b. To better control spatial effects, the IKO's setup can be fine-tuned by ear to the given environment.

Existing compositions have been presented at festivals in configurations like these, including Insonic2015 in Karlsruhe, the International Summer Course for New Music in Darmstadt (2015), the International Computer Music Conference (2012), and in venues such as House of World Cultures in Berlin, the Center for Art and Media (ZKM) in Karlsruhe, the House of Music and Music Drama (MUMUTH) at the University of Music and Performing Arts Graz (KUG), the European Forum Alpbach, and the French Pavilion in Zagreb (shown in Figure 1).

After many concerts performed with the IKO, listeners reported having perceived auditory objects that move away from the IKO and that can have various shapes and layerings, often described as sonic sculptures or (borrowing a term from the visual arts) as "plastic."

The appearance of the terms "sonic sculpture" and "plastic sound" could be a starting point for the research in this field. They are used in compositional practice (Wishart 1996; Gonzáles-Arroyo 2012), can be found in theoretical writings (Emmerson 2000; Ihde 2007; Peters 2010), and have been used in many places in the history of organized sounds and computer music. Examples include Max Neuhaus's "Time Square" installation, described as a sonic sculpture by Collins, Schedel, and Wilson (2013); Bill Fontana calls his works

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Figure 1. The icosahedral loudspeaker (IKO) in the French Pavilion of the Student Centre Zagreb at the Showroom of Contemporary Sound Festival 2015. (Photo by Kristijan Smok, Zagreb.)

Figure 2. Staging constellations of the IKO: rectangular (a) and concave (b).

Figure 1

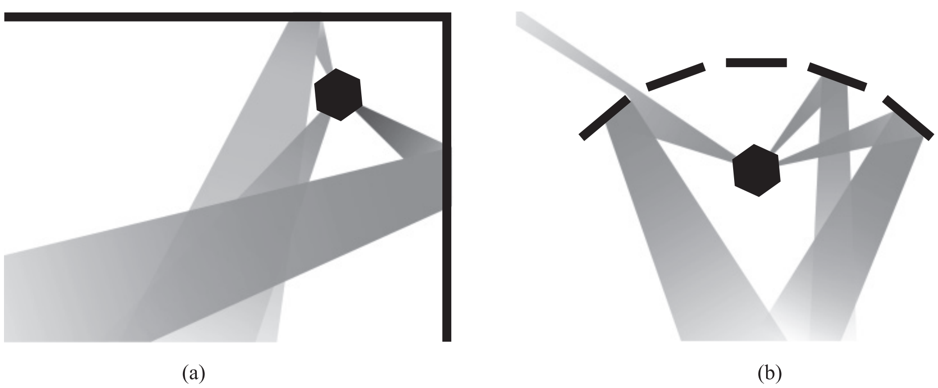


Figure 2

sound sculptures (see www.resoundings.org); and Jonty Harrison (1998) writes of sonic sculptures in connection with the sound diffusion. Moreover, considering the fact that a well-known musical software tool is called AudioSculpt (http://forumnet.ircam.fr/product/audiosculpt-en), this clearly hints both at a prevalent idea of sound as sculptural material and at the composition of electronic music as an act that can be linked to sculptural field within the fine arts. Thus in the musical context, the use of these terms oscillates between extended sonic objects, loudspeaker constellations, and sound as a sculptural material itself, reminding one of Edgar Varèse's planes, shapes, and zones of intensities (Varèse 2004).

If we examine some of the historical body–space relations that have been distinguished in the theory of sculpture (Klant and Walch 2014), several relations between matter and space might be useful in spatialized computer music. What we can say axiomatically is that "a body" or "matter" is opposed to an infinite space (Krämer 2011). Both exist in a reciprocal relation. We can further observe that, historically, the sculptured body volume opens step by step towards space, trying to invade it until finally almost dissolving into it. That means that space is not just a surrounding shell or an envelope but, since modernity, it is an active cocreator of sculpture. Without detailed empirical musicological study we might assume a similar idea of spatial sound composition, especially in the case of electroacoustic music over the last several decades, where space became a parameter on an equal footing with timbre or rhythm (Bayle 2007; Smalley 2007; Nyström 2013).

Using a terminology derived from the theory of sculpture, we still lack a specific denotation for types of sonic sculptures that best represents how they are percieved. First, this raises the question whether such entities are perceived at all intersubjectively, as intended by the composer, causing something we call a shared perceptual space (Sharma, Zotter, and Frank 2015). This space is defined as an open set of spatiosonic phenomena for which the perceptions of composers, scientists, and audience intersect.

Strictly speaking, objective evidence regarding the qualities of perceived sculptural sonic objects can only be accessed systematically through listening tests, but until now tests have only seldom been applied (Landy 2007).

To resolve the question of whether the IKO's auditory objects and sculptures are intersubjectivley perceivable (as well as the question of which ones), we performed listening tests. Based on the results, we propose a classification of complexity levels. The levels characterize sculptured auditory objects, and categories of plastic sound objects and can be seen as composition elements. This might provide a basis for common verbalization. Moreover, doing so resolves the question of whether (and which of) the IKO's auditory objects and sculptures are intersubjectively perceivable. Finally, we propose a classification of complexity levels concerning sculptured auditory objects and categories of plastic sonic objects. These can be seen as composition elements and might provide a basis for a common vocabulary.

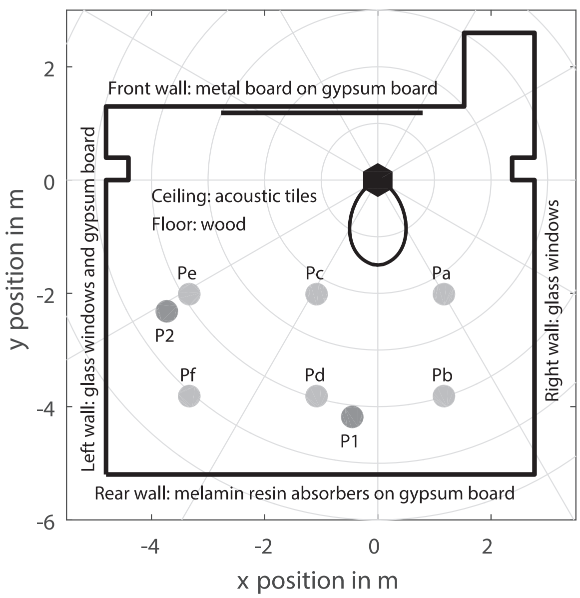
Experimental Framework and Setup

A general approach to the spatial perception of sound can be found in the psychoacoustic literature. A comprehensive review of this issue is provided by Jens Blauert (1983). More specifically, the work of Rakerd and Hartmann examines the localization of sound in reverberant environments, such as rooms (Hartmann 1983; Rakerd and Hartmann 1985, 1986; Hartmann et al. 1989). A fundamental phenomenon of localization is the precedence effect. It refers to a group of phenomena that are thought to be involved in resolving the competition for perception and localization that occurs between temporally delayed sounds with partial coherence, such as a direct sound and a reflection. Comprehensive reviews approaching the precedence effect were conducted by Litovsky et al. (1999) and by Brown, Stecker, and Tollin (2015). In addition, localization effects of the IKO in rooms can be partly deduced by the work on localization in surrounding loudspeaker arrays at off-center listening positions reported by Frank (2013) and by Stitt (2015). More specific studies dealing with the properties of auditory objects created by variable directivity in a room are still fairly new (cf. Schmeder 2009; Sharma, Zotter, and Frank 2014; Zotter et al. 2014; Frank, Sharma, and Zotter 2015; Laitinen et al. 2015; Zotter and Frank 2015; Wendt et al. 2016).

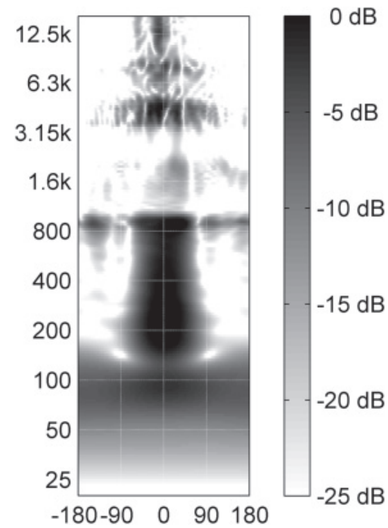
For the purpose of this article, sculptural sonic objects, considered as artistically designed entities, can consist of several time-variant spatiospectral elements. Owing to the combinatorial explosion with this number of elements, an exhaustive investigation would not be practicable. To overcome this problem of complexity in our experimental design, we used a hierarchical model of spatiosonic phenomena consisting of three levels:

1. First-order phenomena, consisting of a single static percept (i.e., a shape or object) triggered by a simple element (in the aforementioned sense) by time-invariant spatial projection.

Figure 3. Setup of the listening experiments (a) and frequency-dependent beam patterns of the IKO (b). The room layout shows the position of the IKO with its directivity pattern, the listening positions (P1, P2, and Pa–Pf), and the materials used for the six main boundary surfaces. For the beam patterns we used a third-order, horizontal beam steered to 0° over frequency (in Hz) and azimuth angle (in degrees) on the horizontal plane; dB levels represented as shades of gray.



(a)



(b)

These fundamental phenomena are easy to explain or investigate on the basis of psychoacoustic research.

2. Second-order phenomena, consisting of time-variant spatial projections with similar excitation signals. Instances of such projections can be trajectories such as turns, pendulums, or movements of greater complexity.
3. Third-order phenomena, which superimpose several first- and second-order phenomena and lead to complex spatiosonic objects—sonic sculptures as artistic entities.

These three phenomena are investigated in a series of three listening experiments, which we describe later in this article.

In contrast to experiments that examined localization effects of a virtual realization of the IKO with simplified settings (Zotter and Frank 2015; Wendt et al. 2016), the experiments we present in this work were conducted in a physical room, a lecture hall with the dimensions 6.8 × 7.6 × 3 m.

The IKO was placed near the corners of the room, which corresponds to a rectangular performance situation. To investigate the influence of the listening position on spatial sonic phenomena, the subjects performed the tests at various listening positions. Figure 3a shows the layout of the room, indicating the positions of IKO and listeners (in Experiments 1 and 2 these are labeled P1 and P2; for Experiment 3, the labels Pa–Pf are used), and lists the materials of the six main boundary surfaces. It is safe to assume that in this room most of the reverberant energy is caused by reflections of the three frontal walls, whereas the rear wall has a higher absorption coefficient. Table 1 lists the mean reverberation time, T_{60}, measured at both listening positions in octave bands defined by the center frequency f_c.

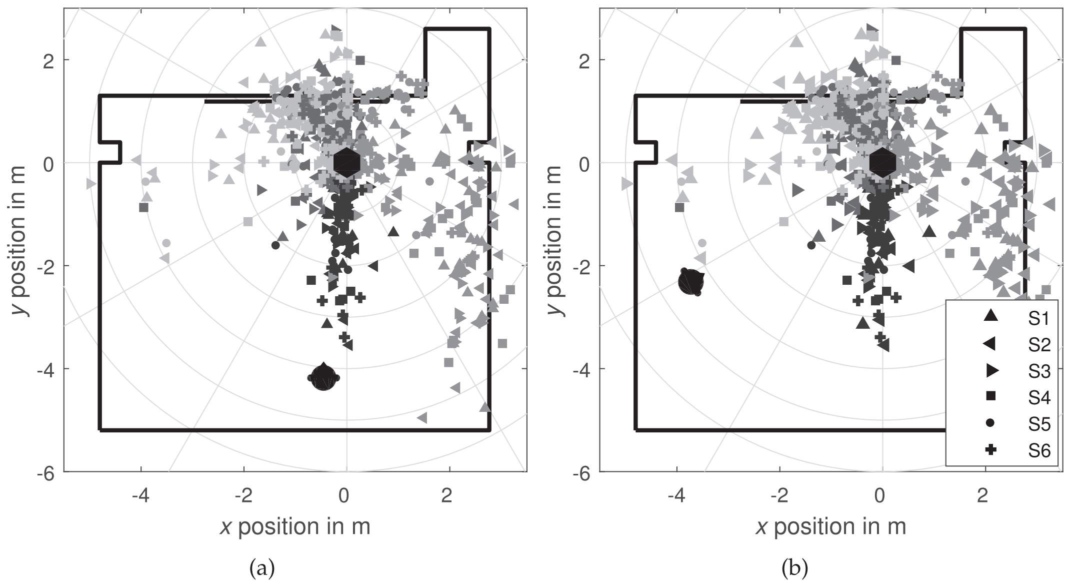
Table 1. Mean Reverberation Times

f_c	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
T_{60}	800	600	530	500	500	540

Reverberation times (in msec) measured at listening positions P1 and P2 for six consecutive octave bands.

The IKO uses "spherical beam forming," as developed by Zotter (2009) and Lösler (2014). This yields beam patterns that are slightly frequency-dependent and with relatively narrow width. The result for a horizontal third-order beam is shown in Figure 3b.

Figure 4. Answers collected at listening positions P1 (a) and P2 (b) for four third-order beams, coded in grayscale. See Figure 5 for coding of tested beam directions.



Listening Experiment 1

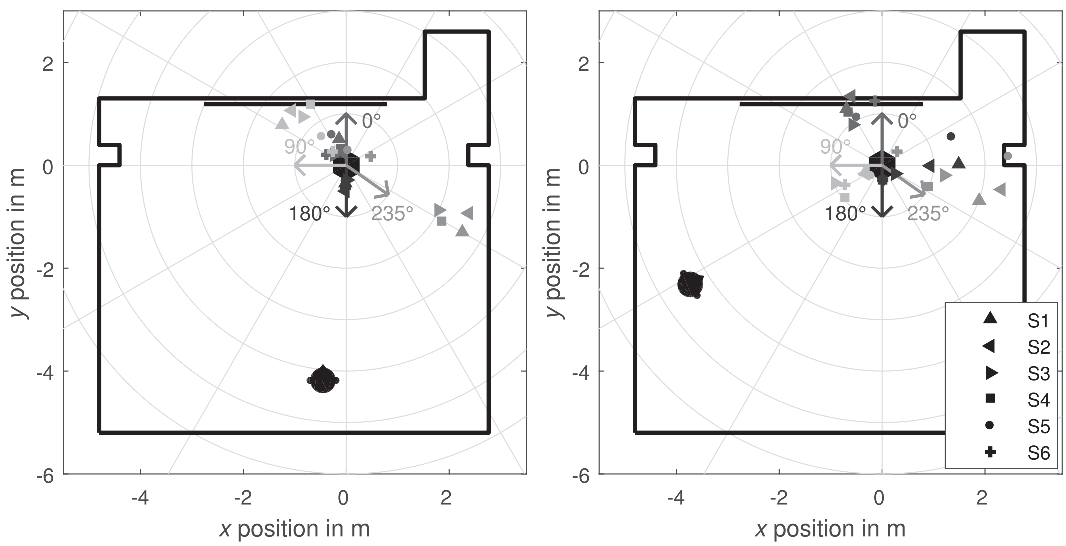
The first listening experiment investigates whether the IKO is able to create an intersubjective spatial perception of different projections. In particular, localization is evaluated for static sound beams projected towards various azimuth angles.

Sound projection was achieved by four different, third-order spherical beams at azimuth angles of 0°, 90°, 180°, and 235° (delineated in Figure 4). Pink noise bursts with four combinations of two different durations for the onset and release times ($t_{short} = 10$ msec, $t_{long} = 500$ msec) were chosen as sounds. Although broadband noise can be problematic in simple localization tasks (multiple locations may be perceived), pretrial experience revealed that it is possible to identify one dominant auditory object whose location is, however, influenced by the shape of the envelope. The critical effect of envelope indicates that localization is determined by the buildup of the precedence effect rather than by summing localization (Litovsky et al. 1999; Brown, Stecker, and Tollin 2015). This assumption is further supported by the magnitude of time delays between direct sound and wall reflections (6 msec $< \Delta t <$ 30 msec at both listening positions).

As a result of these considerations, envelope shapes were identified as meaningful parameters for the burst signal of pink noise. Each of the pink-noise sounds, denoted S1–S4, is represented by a marker whose outline indicates the envelope shape (i.e., S2, which exhibits a slow onset and short release, is represented by the symbol ◀; see Figure 4). Sound 5 (S5, represented by the symbol +) consisted of a sequence of irregular short bursts, and Sound 6 (S6, represented by ●) was a chain of overlapping regular grains. For each run, subjects were seated at one of the two listening positions (P1 and P2), facing the IKO. Subjects were free to move their heads while seated. The binaurally rendered stimuli, using the virtual IKO (Zaunschirm, Frank, and Zotter 2016), are available on our Web site (P1 at https://phaidra.kug.ac.at/detail_object/o:34849, P2 at https://phaidra.kug.ac.at/detail_object/o:34853). The listeners were asked to specify azimuth angle and distance of the dominant auditory object within an IKO-centric coordinate system. With the successful reduction to a single percept, the general controllability of auditory objects is shown.

Fifteen experienced listeners with normal hearing participated in the experiment. Seven selectable stimuli, of which six belonged to different sounds with randomly selected direction, were shown

Figure 5. Median values for the localization results shown in Figure 4, for positions P1 (a) and P2 (b). Medians are calculated for each sound and beam direction (arrows indicate corresponding beam angles).



(a) (b)

together on one screen to allow comparative responses. The seventh stimulus was a randomly selected repetition of one of the other six stimuli on the screen. With four such screens per listening position, each of the 15 participants gave two to four responses per stimulus. In total, all listeners gave 420 responses per listening position, as shown in Figure 4. Sounds are coded as marker shapes and beam direction by different shades (see Figure 5 for the coding of beam direction).

Results

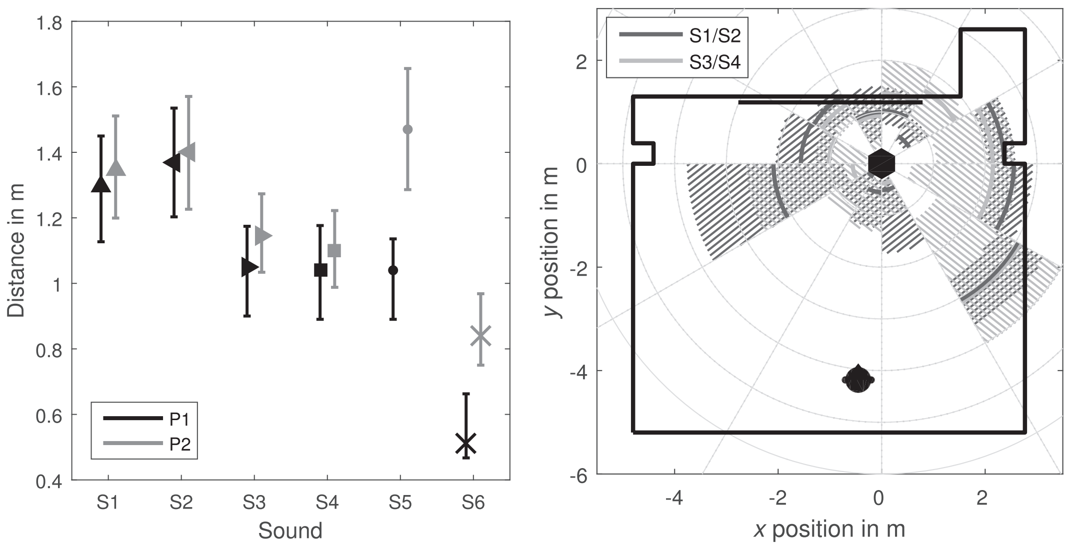
The distinct shades of the marker cloud in Figure 4 indicate the different intersubjective perceptions of various projections. This is supported by the two-dimensional median values shown in Figure 5.

A pairwise analysis of variance (ANOVA) of all azimuth angles for each beam direction confirms the different perceptions of various angular projections. For both positions, all six sounds yield at least three different directions ($p < 0.05$). For some conditions, however, neighboring directions are perceived to be statistically identical ($p > 0.95$). According to the ANOVA for P1, beam directions 0° and 90° tend to coincide, and for P2 the directions 180° and 235° coincide.

The distance of auditory objects to the IKO is the second parameter analyzed in the experiment. Figure 6a shows the 95 percent confidence intervals of the perceived distance for all conditions. The perceived distance of sounds $S1$–$S4$ depends on the onset duration ($p_{S1S2/S3S4} = 0.0017$). Similarly, the irregular bursts (S6) are localized closer to the IKO than the grains (S5). This can be explained by a higher proportion of transient signal components within S6. Both dependencies support findings on the specific properties of the precedence effect for transient signals (see Hartmann 1983; Rakerd and Hartmann 1985). We see, moreover, that auditory objects are perceived closer to the IKO for listening position P1 than for P2 ($p = 0.002$).

A combined presentation of azimuth angle and distance as dependency of the onset (long onset: S1–S2; short onset: S3–S4) can be found in Figure 6b, where the angular distribution of the median distance (including interquartile ranges) is shown for listening position 1. Except for the zone behind the IKO, S3 and S4 are localized being closer to the IKO.

Figure 6. Perceived distance of auditory objects to the IKO: median and 95 percent confidence interval of perceived distance to the IKO over all beam directions (a); median and interquartile range for stimuli S1/S2 (long onset) and S3/S4 (short onset) at P2, equally split on twelve circular segments around the IKO (b).



(a) (b)

The results of Listening Experiment 1 show that the IKO is able to trigger controlled auditory objects in space by using spherical beam-forming algorithms. Depending on its staging and the listening position, different zones around the IKO can be "orchestrated." The perceived distance (and therefore, the reachable spatial extent of the auditory scene) is signal-dependent. We have shown that the more transient signals, i.e., signals with short onset durations, tend to be localized closer to the IKO than smooth signals.

Listening Experiment 2

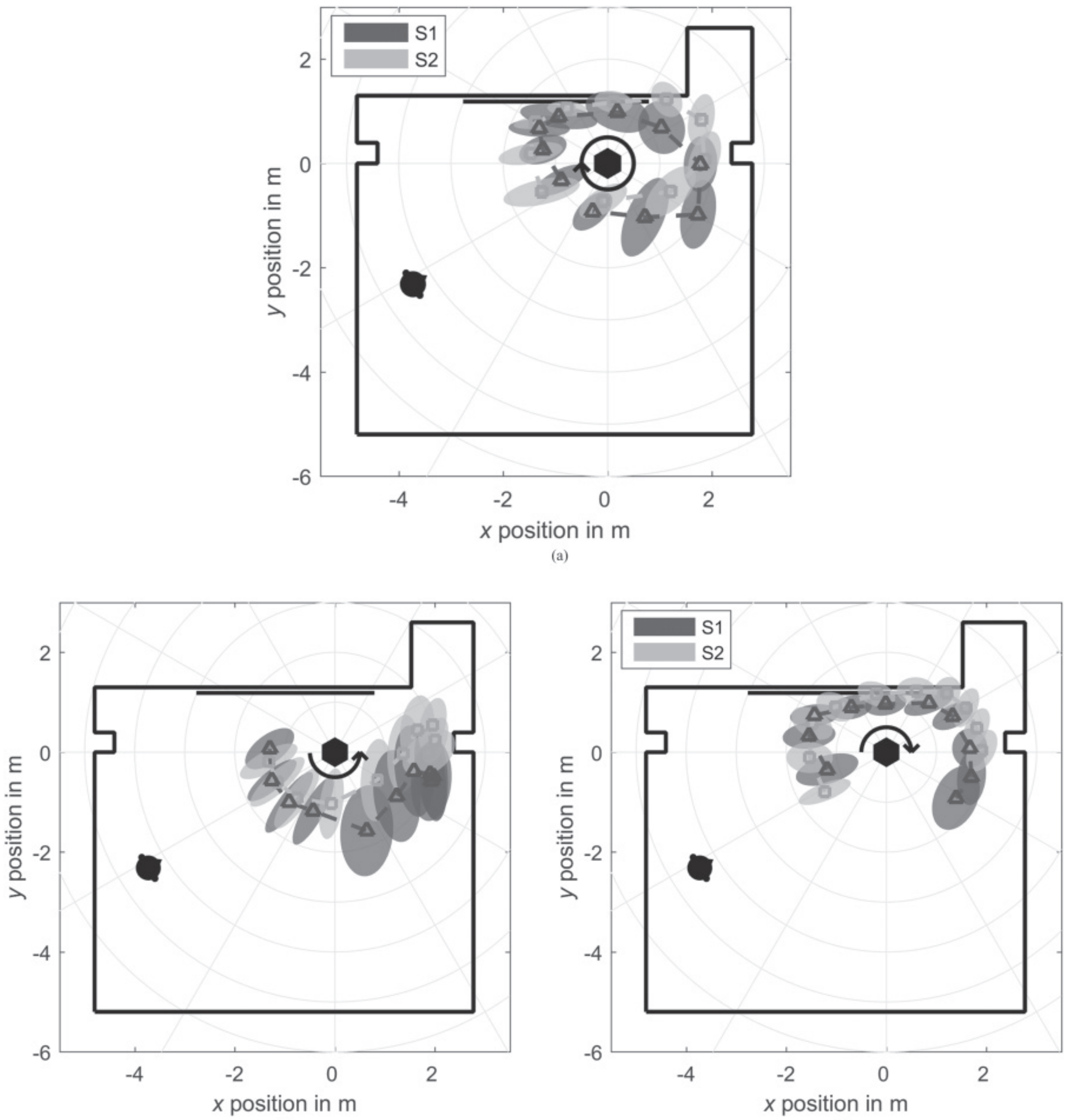
The second listening experiment evaluates the perception of trajectories of sound beams.

The creation of time-variant spatial projections is a further means of expression and hence a further step towards the orchestration of space. A narrow beam rotating in the horizontal plane of the IKO is a rather simple realization of this kind of projection. Three different realizations of this trajectory have been investigated in the second listening experiment: a full turn and two half turns in opposite directions, all starting at 90°, shown in Figure 7.

Each trajectory lasted 5 sec and the subjects were asked to adjust ten markers to the perceived location in successive half-second intervals during playback. Markers were flashed successively at the associated playback time, and they could be moved using a mouse on a graphical interface showing the layout of the test setup. Playback could be repeated until listeners were satisfied with the match between marker placement and what they heard. Room and positioning of the IKO and listener remained the same as for Listening Experiment 1. Because of the relation between onset duration and perceived distance, two variant bursts of pink noise were tested. Sound 1 (S1) consisted of uniform pink noise representing an infinite onset duration. Sound 2 (S2) consisted of 200-msec bursts of pink noise, each with a linear fade-in and fade-out of 10 msec each, and with 100 msec of silence between bursts. Additionally, irregular bursts (S3) and grains (S4), as in the previous experiment, were tested.

Again, the experiment was carried out using 15 experienced listeners with normal hearing. The stimuli S1–S4 were played in random order for both listening positions, each one with a clockwise half turn, a counterclockwise half turn, and a

Figure 7. Mean and 95 percent confidence area for S1 and S2 at listening position P2: full turn of 360° (a), turn of 180° counterclockwise (b), and turn of 180° clockwise (c).



full turn. The binaurally rendered stimuli for this experiment are also available online (P1: https://phaidra.kug.ac.at/detail_object/o:34854; P2: https://phaidra.kug.ac.at/detail_object/o:34856).

Results

For representation of the collected data, a two-dimensional plot for each time step shows its mean

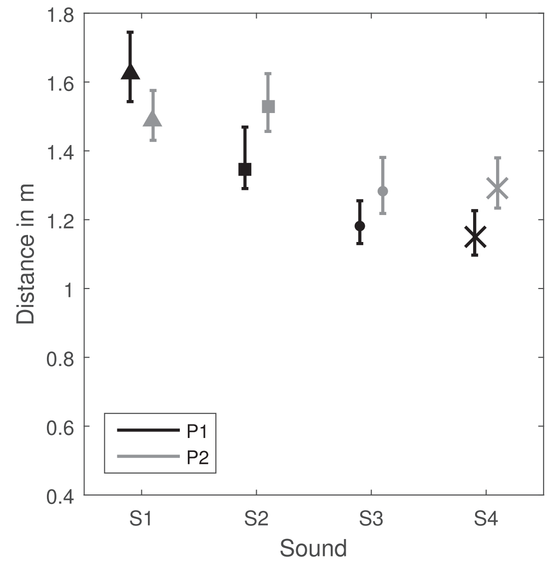


Figure 8. Mean and 95 percent confidence interval of perceived distance over all trajectories.

value within the 95 percent confidence area (see Figure 7).

The circular trajectory is reflected by almost perfect circles around the IKO, obtained by the mean values of the collected data of both listening positions (see Figure 7a). Furthermore, the 95 percent confidence areas are almost equally spread around the IKO, which is in contrast to the findings from Experiment 1, where localization could not fully encircle the IKO. Not only does the full turn deliver smooth results, but the half-turn trajectories shown in Figure 7 also track the idea of the spatial movement.

In contrast to the responses to the trajectory of the full turn, which match the angular range presented to the listener, the responses to the half turns were larger than the semicircle presented. This effect could be caused by the slower angular speed of the spherical beam (half as fast as for the full turn), or the effect could be due to a psychoacoustic phenomenon called "auditory representational momentum" (Getzmann and Lewald 2007), which describes the displacement of the final position of a moving sound source in the direction of motion. A thorough review of phenomena in the perception of auditory motion is documented by Carlile and Leung (2016).

Comparing the perceived distance of auditory objects for the different signal onsets (S1 and S2), the results at listening position P1 indicate that transient signals with short onsets are perceived closer to the IKO than signals with smoother envelopes ($p_{P1} < 0.001$; see Figure 8), and so confirm the findings of Experiment 1. This is in contrast to the results for position P2, however, where Figure 7 does not indicate any envelope dependency. Furthermore, the findings of Experiment 1—that at P2 auditory objects are generally perceived further away from the IKO than at P1—is not as pronounced in this experiment ($p_{S1\ldots S4} = 0.200$). Excluding S1, however, the other results were as statistically significant as in Experiment 1.

Finally, a direct comparison of all collected data from Experiments 1 and 2 shows that the perception of trajectories cannot be fully explained by extrapolating the perception of static sound beams. It seems that listeners try to understand the intended auditory motion and thus experience a more comprehensive percept.

Listening Experiment 3

The third listening experiment evaluates what we call third-order phenomena. These are composed of several sounds that are spatialized in different directions and with different angular movements. More specifically, it is an evaluation of the ability to discriminate stimuli based on their spatiosonic character. With this first step towards exploring the composition of sonic sculptures, insights on the existence of a shared perception of spatiosonic objects are gained.

To arrive at artistically meaningful and musically expressive spatiosonic objects, composer and coauthor Gerriet K. Sharma designed the stimuli of this experiment making use of his experience and means of expression developed for the IKO. Building on this experience, he arrived at an understanding of spatiosonic objects in terms of body–space relationships deduced from the theory of sculpture. Following Torsten (Krämer 2011), we distinguish three main categories of body–space relationships, which we call *kernel plastic* (abbreviated KP), *spatial plastic* (SP), and the *kernel–shell principle* (KSP).

Table 2. Composition of Stimuli

	Element 1		Element 2	
Stimulus	*Sound*	*Trajectory*	*Sound*	*Trajectory*
KP_I	BN	180°, static		
KP_{II}	LFD	180°, static		
KP_{III}	SMS	0°, static		
KP_{IV}	LFD cut	210°, static	SMS	210° static
SP_I	BN	CCW 237°/sec rotation		
SP_{II}	LFD cut	CCW 140°/sec rotation		
SP_{III}	SMS	CW 180°/sec rotation		
SP_{IV}	CG	CCW 270°/sec rotation		
SP_V	LFD	CCW 120°/sec rotation		
KSP_I	BN	CCW 180°/sec rotation	BN cut	CW 180°/sec rotation
KSP_{II}	BN	305°, static	BN del	CW 180°/sec rotation
KSP_{III}	LFD cut	CCW 180°/sec rotation	SMS	CW 180°/sec rotation

Elements used to compose the stimuli for Listening Experiment 3 are: constant Brown noise (BN), filtered Brown noise with a low-pass cutoff frequency at 2,426 Hz (BN cut), Brown noise with the same cutoff and a delay of 15 sec (BN del), a low-to-mid-frequency drone (LFD), the drone with a high-pass cutoff frequency at 236 Hz (LFD cut), a multilayered, stretched metal sound with long onset and release (SMS), and a chain of fine regular grains (CG). The direction of movements are either clockwise (CW) or counterclockwise (CCW). All angles are in the horizontal plane around the IKO. The stimulus categories KP, SP, and KSP are described in the article.

Kernel plastic (or "body plastic," taken from the German terms *Kernplastik* and *Körperplastik*) is used to describe objects with the attribute of "superseding" space (*raumverdrängend*). An analogous example from the visual arts would be Auguste Rodin's *The Thinker* (1902). Spatial plastic (*Raumplastik*) describes those objects with the attributes of "encompassing" or "binding" space (*raumumfassend*, *raumbindend*). An example of this would be Naum Gabo's *Linear Construction in Space No.2* (conceived 1949, executed 1959–1960). Finally, the kernel–shell principle (*Kern-Schale-Prinzip*) describes objects that "embody" space (*raumbildend*). Here, an appropriate example might be Henry Moore's *Mother and Child: Egg Form* (1977, LH 717).

The last of these categories embodies the idea of creating space by establishing a tension between two entities, for instance, a focused entity inside and environmental coordinates at the same time.

These categories have provided meaningful hermeneutics for artistic practice over decades.

Sharma composed a set of twelve spatiosonic miniatures along his artistic interpretation of the categories of body–space relations ($KP_{I...IV}$, $SP_{I...V}$, and $KSP_{I...III}$). The material used for the creation of the twelve stimuli was composed from four different sound sources. The idea was to use easily recognizable idioms, similar to the stimuli from preceding experiments, but with a more musical quality to bridge the gap between the laboratory situation and more performative situations. The stimulus composition and grouping is shown in Table 2. Each of the stimuli had a duration of 30 seconds. To test the ability of listeners to naively discriminate between sculptural categories, neither the hierarchical organization scheme nor the composer's categories were known to the listeners. This served to eliminate the potential side effect of interpreted terminology.

Table 3. Permutation of Stimuli in Triplets

Triplet	*1*	*2*	*3*	*4*	*5*	*6*
Stimulus 1	KP_{I}	KP_{III}	SP_{II}	SP_{IV}	$\mathbf{KSP_{II}}$	KSP_{III}
Stimulus 2	$\mathbf{SP_{I}}$	KP_{IV}	SP_{V}	SP_{I}	SP_{III}	KSP_{I}
Stimulus 3	KP_{II}	$\mathbf{KSP_{I}}$	SP_{III}	$\mathbf{KP_{II}}$	SP_{V}	$\mathbf{KP_{II}}$

Listening Experiment 3 used triplets of the stimuli defined in Table 2. The "odd-man-out" stimulus in each triplet is highlighted in ***boldface****. Triplet 3 consisted of three stimuli from the same category, serving as a control condition in the listening experiment.*

The ability to discriminate between perceived sculptural shapes was tested by a three-alternative, forced-choice method (also known as "oddity" or "one-man-out"; cf. Kingdom and Prins 2010). Each stimulus triplet consisted of two stimuli from one category and one stimulus from another category. The stimulus triplets were then presented twice consecutively in a single joint listening session, in which all subjects took part. The listeners were asked to indicate the stimulus that differed from the others by its spatial appearance. As a control condition, Triplet 3 comprised stimuli from a single category. Table 3 shows the triplets tested.

The listening session was conducted twice, each time with six subjects, all of whom were familiar with computer music and were experienced listeners to spatial audio. To monitor possible impacts of the listening position, the listeners were spread within the room (at positions Pa and Pb, see Figure 3a) and changed their position after the first run. Additionally five of the six subjects evaluated the same triplets using mono playback over headphones. Because there is no spatial difference within the triplets, subjects were requested to discriminate between them on the basis of arbitrary characteristics. The playback order of the triplets itself and of the stimuli within triplets was chosen at random. The stimuli are all available on the Web. The monophonic stimuli are at https://phaidra.kug.ac.at/detail_object/o:34857, binaural stimuli from position P1 at https://phaidra.kug.ac.at/detail_object/o:34859, and the binuaral stimuli at P2 at https://phaidra.kug.ac.at/detail_object/o:34860.

Results

A direct comparison of the results for both playback methods provides insights into the impact of spatialization on the ability to discriminate between different types of sonic materials. Response frequencies for Listening Experiment 3 are shown in Table 4.

For all test triplets played in the IKO, listeners identified one stimulus as the oddity, on average agreeing at least 83 percent of the time. Triplet 3, the control triplet, however, did not produce a clear agreement. For the triplets in the monophonic playback over headphones, there was, on average a strong agreement of at least 90 percent on the oddity. Comparing the results of playback inside the IKO with monophonic playback, there is little correlation regarding stimuli recognized as oddities, despite both stimulus sets being based on identical sonic material. The additional spatial character when using the IKO therefore seemed to dominate in recognizing the intended oddity stimulus within the triplets. The exception was Triplet 2, where the same stimulus was recognized.

As none of the listeners were aware of hierarchical spatiosonic phenomena or the composer's categories, we do not know which feature they used to distinguish the odd stimulus. We can not establish a causal relation, but the listeners' perceptual distinction agrees almost completely with the differentiation intended by the composer and the categories he used.

Conclusion

In this article we successfully provided a comprehensive experimental evaluation of sonic phenomena evoked by the IKO. A hierarchical model of spatiosonic phenomena was proposed and validated by extensive listening experiments.

Listening Experiment 1 examined single, static percepts evoked by spatial projections of the IKO. Depending on the staging of the IKO, different zones around it could be "orchestrated." The results revealed where knowledge from psychoacoustic research is applicable to auditory objects. For instance, distance to the IKO is highly dependent

Table 4. Counts of Stimuli Deemed Most Different

triplet	*1*	*2*	*3*	*4*	*5*	*6*
stimulus A	0	1	0	0	**10**	0
stimulus B	**12**	0	5	0	2	0
stimulus C	0	**11**	7	**12**	0	**12**

triplet	*1*	*2*	*3*	*4*	*5*	*6*
stimulus A	0	0	0	4	**1**	1
stimulus B	**0**	0	0	1	4	4
stimulus C	5	**5**	5	**0**	0	**0**

Number of times each stimulus was perceived as "most different" in each triplet. Results using the IKO (left) and monophonic playback over headphones (right). ***Bold*** *numbers mark the stimuli that were designed to have a different sculptural shape.*

on onsets and envelopes. This relation is known from studies on the precedence effect (Litovsky et al. 1999; Brown, Stecker, and Tollin 2015).

Listening Experiment 2 examined phenomena of greater complexity that were evoked by time-variant spatial projections. In contrast to static sound beams, the use of trajectories involves perceptual properties indicated in studies on auditory motion (Getzmann and Lewald 2007; Carlile and Leung 2016).

Listening Experiment 3 investigated the superposition of several phenomena of static and dynamic nature. For this experiment, spatiosonic objects developed by Sharma as means of expression using the IKO were reduced to useful, exemplary categories. Although not generalizable to spatiosonic artistic expression that other composers would develop when using the IKO, and despite the relatively small number of experienced listeners participating, the experimental results are instructive and remarkably distinct. The experimental design proved to be a promising first step to detect intersubjective spatiosonic features that are stronger and more salient as those of nonspatialized sonic materials.

The terminology that the composer developed for the compositions in the last experiment was derived from the theory of sculpture and aims to provide a useful basis for composition and a classification of complex auditory objects that can be created by the IKO. Three categories were proposed, each describing a body–space relationship that can be translated into musical context.

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