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Evaluating a Sonic Interaction Design Based on a Historic Theatre Sound Effect

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Abstract

This paper reports on the procedure and results of a preliminary experiment to evaluate participants' perceptual experiences of a mechanical theatre sound effect and its digital counterpart. The theatre sound effect chosen - an acoustic wind machine - affords a simple rotational gesture; turning its crank handle at varying speeds produces a convincing wind-like sound. A prototype digital model of a working acoustic wind machine was programmed. The mechanical interface of the acoustic wind machine drove both the digital model and its own acoustic sound in performance, therefore preserving the same tactile and kinaesthetic feedback across the two continuous sonic interactions. Participants were presented with two listening tests to examine the perceived similarity of these wind-like sounds and the perceived connection between the speed of the crank handle and the resulting sound. Participants' performances of both the acoustic and digital systems were then elicited with

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sound stimuli produced from simple gestural performances of the wind-like sounds. The results of this study show that, while the sound of the prototype digital model requires further calibration to bring the experience of its performance closer to that of its acoustic counterpart, the acoustic wind machine is significantly easier to play, and the mechanism of its interface may play a role in perceptually guiding performance gestures.
Keywords: Sonic Interaction Design, Digital Musical Instrument, Enactive, Experiment Design, Theatre Sound Effect

1. Introduction

This paper presents the procedure and results of a preliminary experiment designed to evaluate a continuous sonic interaction with a mechanical sound effect, a theatre wind machine, that produces both an acoustic and a digital sound when activated with its crank handle. As simple acoustic interfaces that produce the effect of familiar everyday sounds (Gaver , 1993) like rain, wind and thunder in performance, theatre sound effect designs offer the opportunity to explore the perceptual experience of continuous sonic interactions, and indeed expressive sound performance, without the need for participants to have significant prior experience of musical instrument performance. This study was conducted with the aim of understanding more about the perceptual qualities of the wind machine design, both as a sound source that successfully produces the effect of an everyday sound, and as a sonically interactive device. It also focused on comparing a fully acoustic theatre wind machine with a digitally synthesised model of its sound in order to explore how the simplicity and richness of the original design might be captured digitally.

Despite their sonically interactive qualities, theatre sound effects have not yet been subjected to this kind of evaluation with participants. As such, the experiment protocol described here is grounded in a number of procedures from previous work undertaken in the fields of human perception of environmental sounds, Sonic Interaction Design (SID), and Digital Musical Instrument (DMI) design. In this paper we also examine the effectiveness of the evaluation methods chosen and make suggestions for future studies.

2. Background

Creating a truly embodied, intuitive and perceptually *continuous* interaction with a digital sound presents a challenge for designers. A wealth of research in the fields of Sonic Interaction Design (SID) (Franinović & Serafin , 2013) and Digital Musical Instrument (DMI) design (Jensenius & Lyons , 2017), (Miranda & Wanderley , 2006) has explored the creation and study of new sonically interactive interfaces and systems. Facilitating creative bodily-guided interactions with digital sound would further open its potential as an expressive material without the requirement for prior experience of musical instrumentation or technical skills such as programming. The research presented in this paper is concerned with the interactive potential of digital sound but takes a unique approach to this design problem by examining historical theatre sound effects as a ready-made collection of interfaces that successfully afford truly embodied encounters with acoustic sounds. We propose that studying these designs, creating working examples of them and then modelling them digitally will reveal more about what makes theatre sound effects so intuitive and rich as sonically interactive devices, helping to inform further strategies for continuous interactions with digital sounds (Keenan, F., & Pauletto, S. , 2017b).

Theatrical performances, particularly in the late nineteenth and early twentieth century, relied on acoustic sound effects. Practitioners imitated the sounds of weather, battle or animals using a variety of materials and simple mechanisms (Brown, 2010). The sound of thunder was produced by shaking a long metal sheet hung behind the stage (thunder sheet), while the sound of rain was produced by turning a crank handle to rotate a barrel filled with metal ball bearings (rain machine), for example. Our examination of historical sources on theatre sound effects has shown that, in the absence of an established notation system, performances of these historical interfaces were developed using an approach much like Franinović's (2013) proposed enactive sound design (Keenan, F., & Pauletto, S. , 2017b). This is a Sonic Interaction Design (SID) strategy which engages with the potential of ergoaudition, or listening to self-produced sound (Chion , 2010) to facilitate learning in a sonic interaction. Sound is produced directly and continuously through a user's movement, guiding their sensorimotor activity, and allowing them to build on previously accumulated tacit knowledge of action and sound (Franinović (2009, 2013)). This suggests that theatre sound effect designs made perceptually meaningful connections between actions and sounds (Hug , 2008) for the performers learning to use them through a process of rehearsal, their interfaces potentially building upon a perceived sonic affordance (Altavilla et al. , 2013) of each sound being imitated. There must also have been a perceptually meaningful continuum of energy (Cadoz , 2009) between each performance gesture and its resulting sound effect. It is these design characteristics, as found in the theatre wind machine explored here, that make theatre sound effects a potentially interesting way to facilitate and evaluate continuous sonic interactions.

To examine how the enactive qualities of specific historical theatre sound effects might be uncovered and then captured in the design of a continuous sonic interaction with a digital sound, this research focused on exploring the experience of a continuous sonic interaction with one acoustic sound effect - a theatre wind machine - and comparing this experience with that afforded by a digital model of its sonic feedback. This work extends the methodology used in prior research in the field of SID, which examined the enactive qualities of Luigi Russolo's intonarumori family of early twentieth century acoustic noise instruments in order to recreate them as digital models (Serafin & De Götzen , 2009). The gesture of rotation afforded by the theatre wind machine is itself linked to the production of different sound effects (wind, rain and crashes) (Keenan, F., & Pauletto, S. , 2017b), giving any interface produced as part of this work the potential to control additional digital sounds. It is also unclear how such a repetitive and simple action such as the continuous rotation of a handle could create a perceptually rich interaction with a resulting sound. Historical sources do not explain the origin of the theatre wind machine design, and so this bears further investigation. While the earlier stages of the design work underpinning this study have been described in detail elsewhere (Keenan & Pauletto (2016, 2017a, 2017b)), the final state of the digital model will be briefly summarised here to aid the reader's understanding.

2.1. Interface Design and Synthesis Method

A working example of an acoustic theatre wind machine was constructed from historical design instructions (Keenan & Pauletto (2016, 2017a)). A wind machine (Figure 1) consists of a wooden slatted cylinder mounted on a central axle and A-frame and covered by a cloth. A crank handle coupled to the axle allows a performer to rotate the cylinder. As the handle is turned, the wooden slats of the cylinder scrape the encompassing cloth, which produces a wind-like sound. Historical sources on theatre sound effects practice from the late nineteenth and early twentieth century do not give clear information on the origins of their designs, and little detail on the how an effect might be successfully operated. However, in the case of the acoustic wind machine the speed of rotation of the crank handle is explicitly linked to the quality of the resulting sound (Krows , 1916). An exploration of our working example in performance revealed that this acoustically modelled everyday sound can have perceivably repetitive and machine-like qualities at slow and regular speeds of rotation, but when activated with a gesture of continuously varying speed the sound becomes more convincing as a wind effect. The cylinder of the wind machine has flywheel qualities, storing rotational energy and resisting changes in rotational speed during a performance with its crank handle. This adds complexity to the tactile and kinaesthetic experience of this very simple rotational gesture.

A prototype digital model of this working acoustic theatre wind machine was then programmed in Max/MSP using a procedural approach to sound modelling (Farnell , 2010). This was based on the rubbing and scraping interaction between each wooden slat and the encompassing cloth of the wind

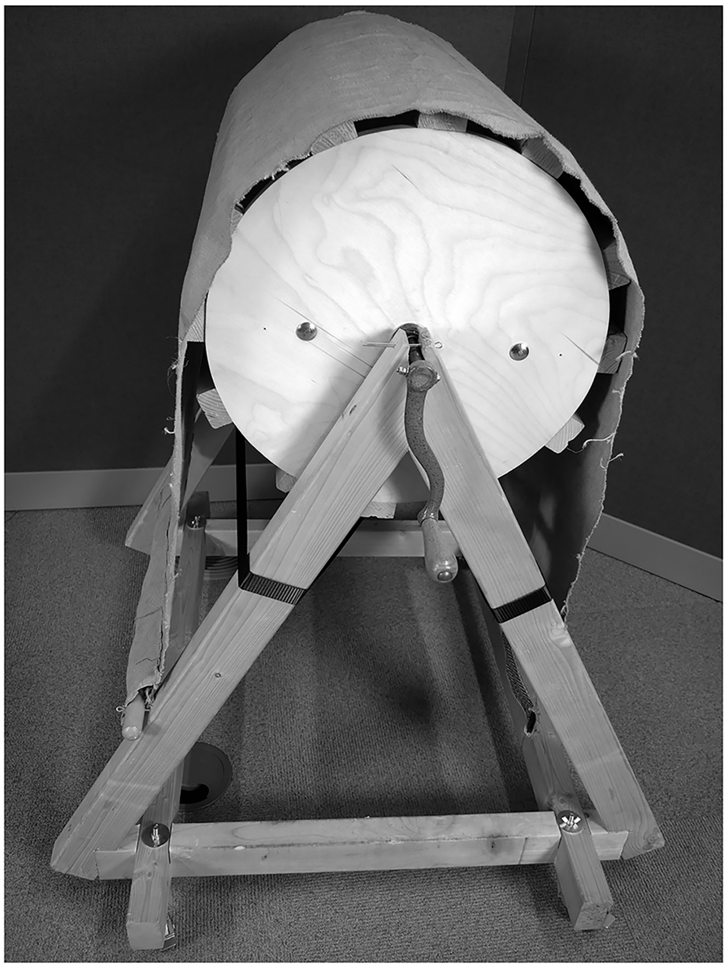

Figure 1: The working acoustic wind machine.

machine during a rotational gesture performed with the crank handle, rather than a physical model of real-world aeroacoustics (Selfridge et al. (2016, 2017)) or a signal-based method using noise and band-pass filters (Farnell , 2010). In this way, the perceptual experience and potential distinctions between real-world wind sounds and the cloth-based effect of the acoustic wind machine could potentially be examined, and the primacy of the performer's gesture in the realism of the wind effect could be transferred more explicitly to the digital prototype. The acoustic wind machine's mechanism was fitted with a rotary encoder, laser-cut gearing and an Arduino to capture data from its rotational motion and use this data to activate the model in Max/MSP. This allowed the acoustic wind machine's crank handle to drive the digital model of its sound in performance, maintaining a consistent tactile and kinaesthetic feedback during a performance of both the acoustic and digital wind-like sounds.

The digital model was based on twelve instances of the Sound Design Toolkit (SDT) physical model of friction (Baldan et al. , 2017) to represent each of the twelve slats of the acoustic wind machine. The single stream of incremental data from the rotary encoder was parsed into the same twelve individual degree positions of the acoustic machine's wooden slats. Rotating the acoustic wind machine's crank handle could now drive a multi-pronged data stream that modelled the movement of the individual wooden slats ahead of or behind the position of the handle, allowing each digital slat model to be activated in a way that mirrored when its acoustic counterpart was in contact with the encompassing cloth. Some additional dispersion of the resulting friction sounds was also implemented to model each side of the

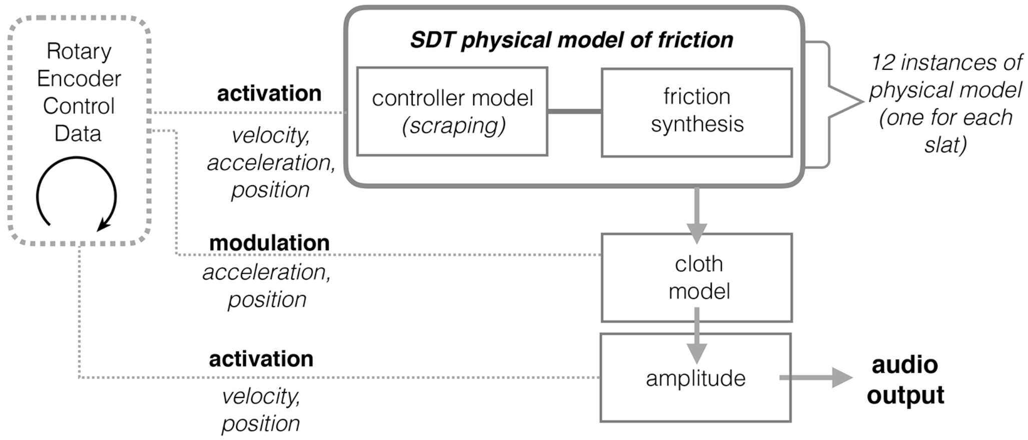

Figure 2: The signal processing architecture and data mapping of the digital wind sound model.

cloth. This consisted of an adapted model of string vibration from Karplus-Strong synthesis (Karjalainen et al. , 1998) to model the tight side of the cloth, accounting for some damping due to its coupling to the acoustic wind machine's bridge. A digital waveguide (Smith , 2010) was used to model the freely hanging side of the cloth. Velocity and acceleration were also calculated from the rotary encoder's data stream, facilitating further modulation of the model's parameters and activation of the overall amplitude envelope of the digital wind-like sound (Figure 2).

As the acoustic and digital wind-like sounds could be simultaneously activated by the same performance gesture, they could also be simultaneously recorded. This process was used to acoustically compare the acoustic and digital wind-like sounds, and also to produce the stimuli used in the experiment with participants reported here. The spectrum of the acoustic wind machine is noisy, but with peaks in the low and mid frequencies and a sig-

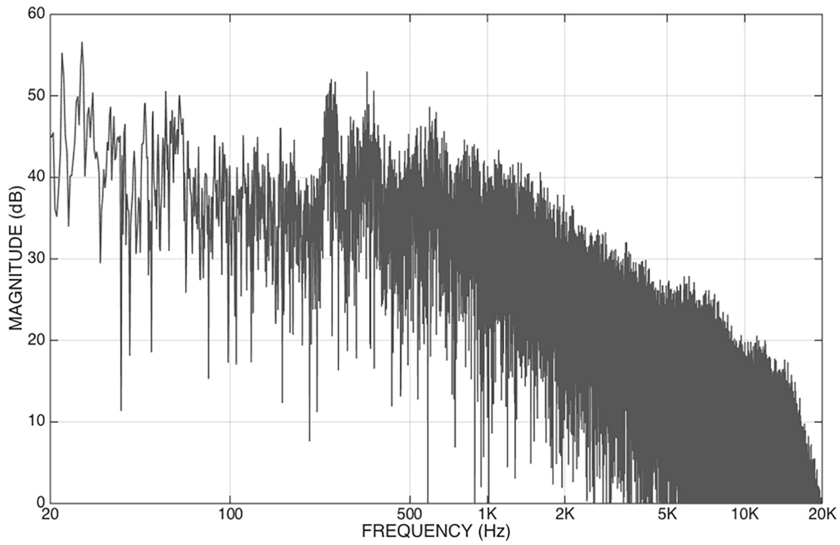

Figure 3: Spectrum of the acoustic wind machine.

nificant amount of high frequency energy (Figure 3). The spectrum of the digital model replicates much of the noisiness of its acoustic counterpart, but with a peak at 1KHz and less high frequency energy (Figure 4).

A comparison of the amplitude envelopes of the acoustic and digital sounds established that the digital model tracked well with its acoustic counterpart for a single rotation of the crank handle (Figure 5, 6).

An analysis of the dynamic evolution of the amplitude envelope and spectra of both sounds produced by varying controls speeds of the crank handle showed that the digital model was responsive in performance (Figure 7, 8, 9, 10), but tracked less well with its acoustic counterpart at more extreme variation in rotational speeds (Figure 11, 12, 13, 14).

The procedure reported within this article was first piloted with six participants. This confirmed that the acoustic wind machine and digital model were both perceived as wind-like sounds before proceeding to the full exper-

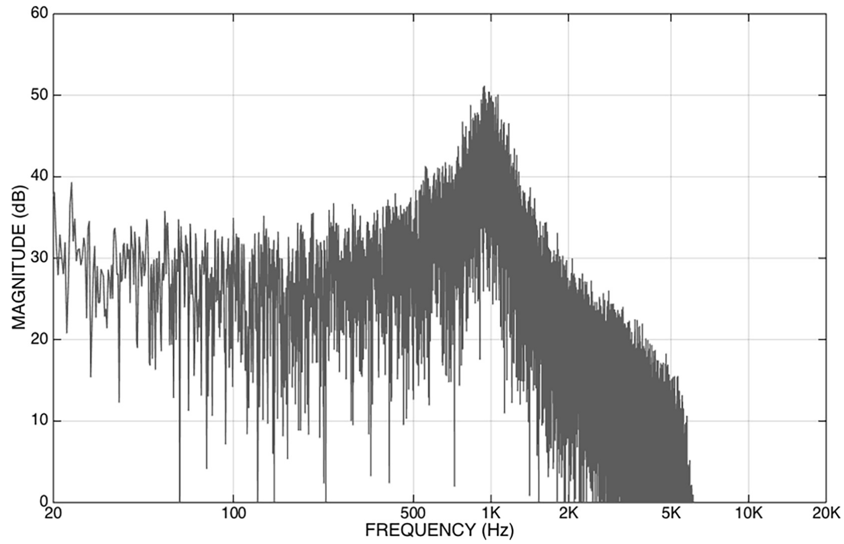

Figure 4: Spectrum of the digital model of the wind machine.

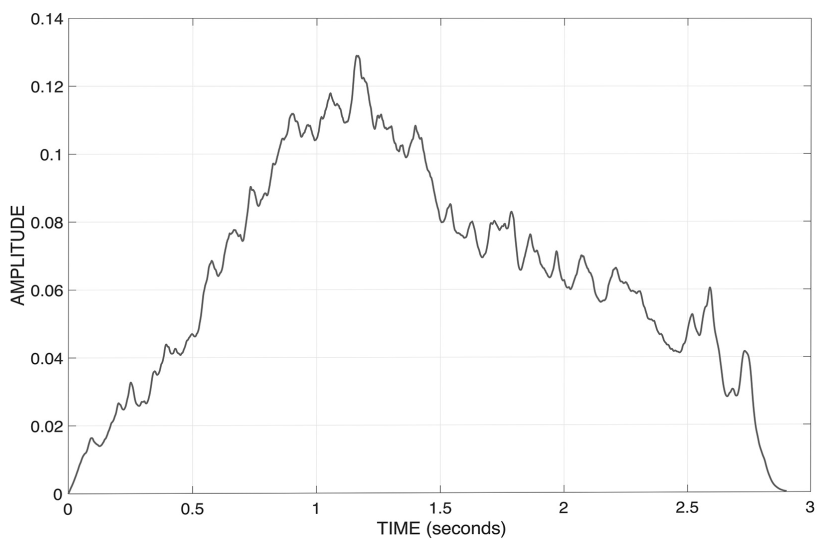

Figure 5: Amplitude envelope of the acoustic wind-like sound for 1 steady rotation.

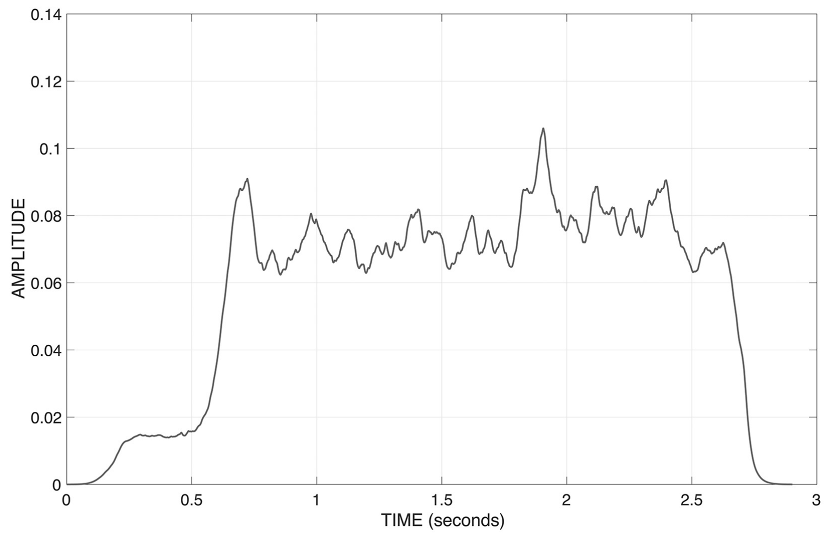

Figure 6: Amplitude envelope of the digital wind-like sound for 1 steady rotation.

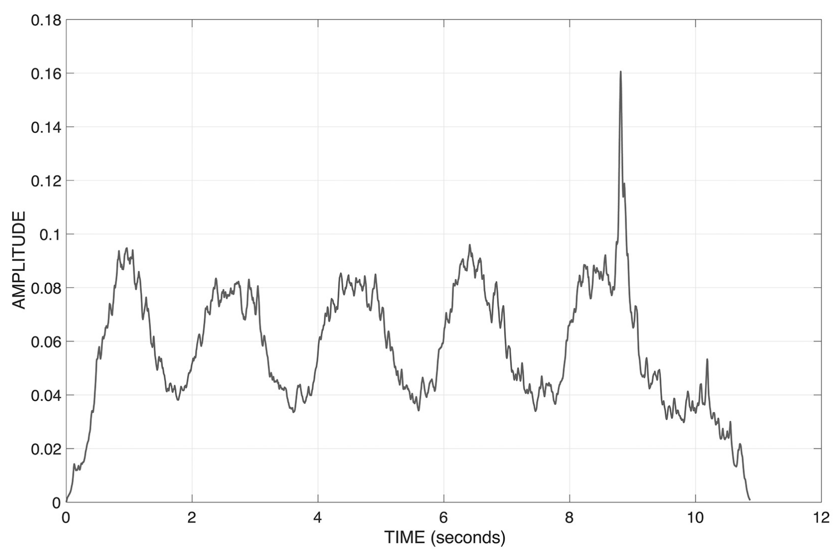

Figure 7: Amplitude envelope of the acoustic wind-like sound for 5 steady rotations.

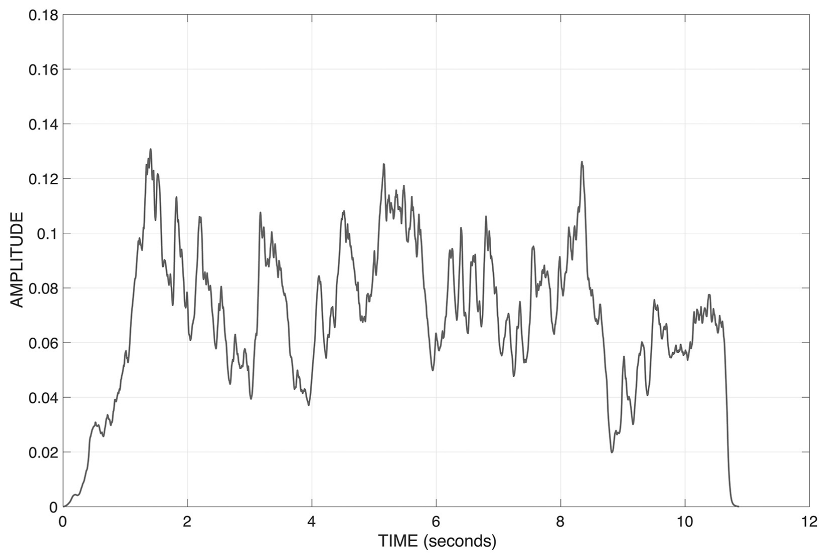

Figure 8: Amplitude envelope of the digital wind-like sound for 5 steady rotations.

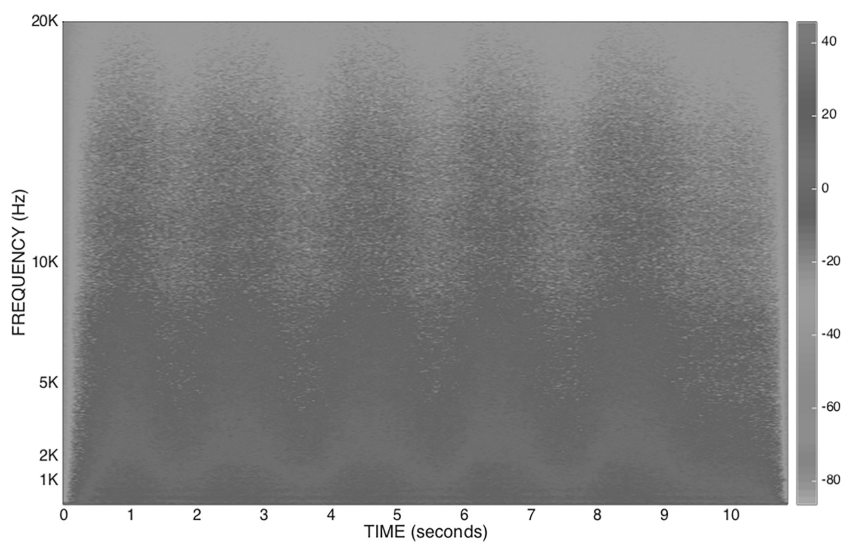

Figure 9: Spectrum of the acoustic wind-like sound for 5 steady rotations.

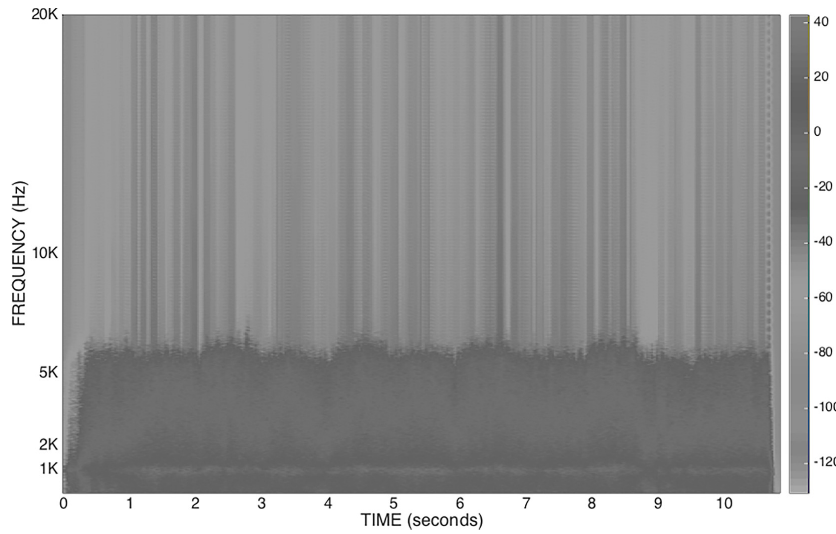

Figure 10: Spectrum of the digital wind-like sound for 5 steady rotations

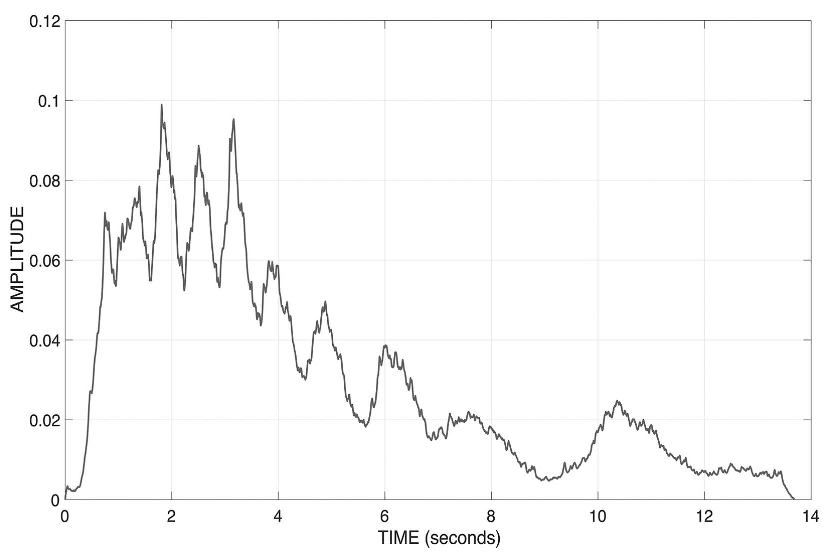

Figure 11: Amplitude envelope of the acoustic wind-like sound for 10 rotations starting at speed and then diminishing in energy.

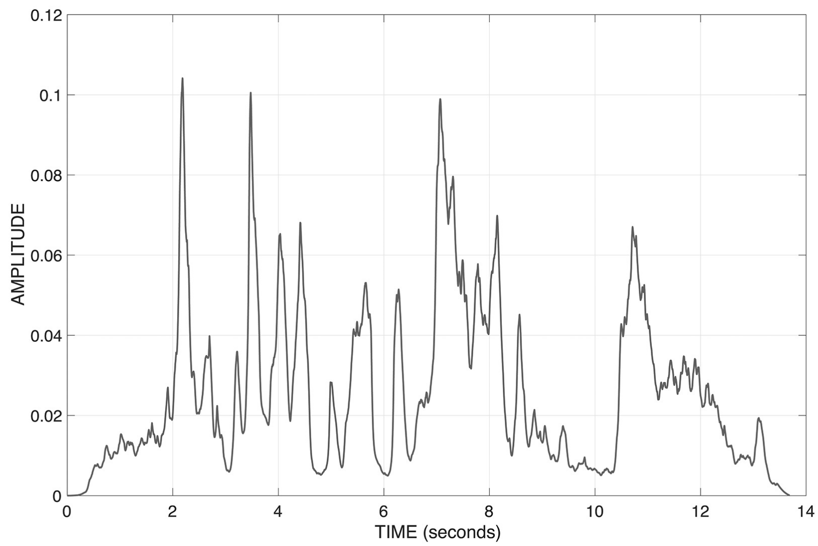

Figure 12: Amplitude envelope of the digital wind-like sound for 10 rotations starting at speed and then diminishing in energy.

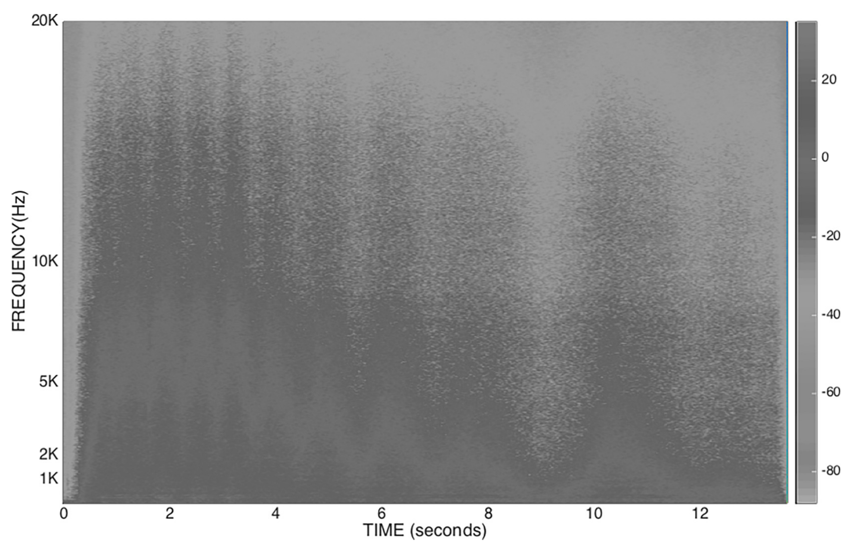

Figure 13: Spectrum of the acoustic wind-like sound for 10 rotations starting at speed and then diminishing in energy.

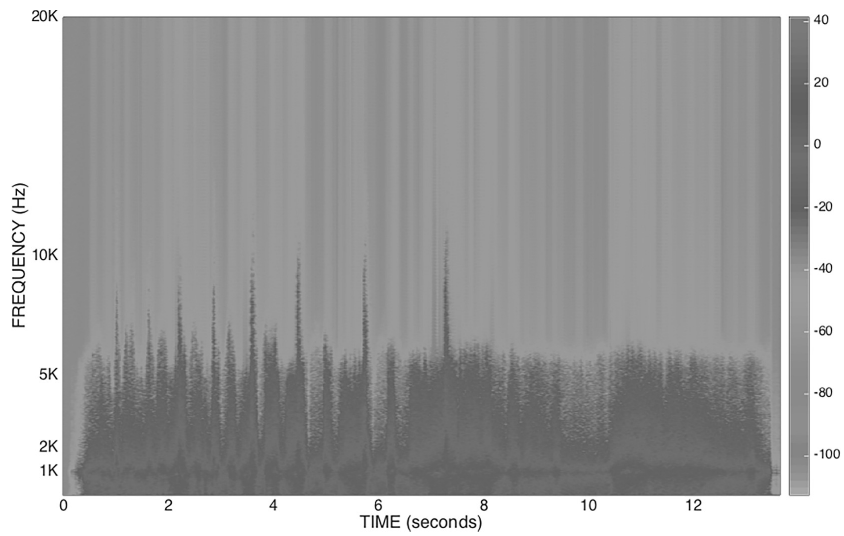

Figure 14: Spectrum of the digital wind-like sound for 10 rotations starting at speed and then diminishing in energy.

iment.

3. Experiment Design

An experiment was designed to compare participants' perceptual experiences of both the acoustic and digital wind-like sounds, and explore the efficacy of evaluation procedures from previous studies in examining the wind machine design more closely. The experiment was designed to include three distinct steps; two listening tests (Steps 1 and 2) and then, following a short break, a performance test (Step 3).

The main hypotheses developed were as follows:

- Hypothesis 1 (H1): There is perceived similarity between the acoustic wind machine sound and the prototype digital wind machine sound. (Step 1)

- Hypothesis 2a (H2a): Participants can perceive different rotational speeds in a continuous wind-like sound produced through acoustic or digital means. (Step 2)
- Hypothesis 2b (H2b): The perception of rotational speed is equally accurate when the continuous wind-like sound is produced through acoustic or digital means. (Step 2)
- Hypothesis 3 (H3): There is perceived similarity between the experience of performing with the acoustic wind machine and that of performing with the prototype digital wind machine. (Step 3)

The full experiment took approximately 40 minutes.

3.1. Step 1: Perceiving Effects Based on Environmental Sounds

Human auditory perception is intimately linked with action. Discrete impacts are perceived as very distinct from continuous sounds like tearing, for example (Gygi et al. (2007) and Houix et al. (2012)). This underlying perceptual structure of a group of sounds can be revealed with similarity ratings (Bonebright et al. , 2005). Gygi et al. (2007) used similarity ratings tasks to show that participants categorise everyday sound events into three distinct clusters (impacts, continuous sounds and harmonic sounds). This produced a matrix of similarity values averaged across the participants, facilitating multidimensional scaling (MDS) analysis to produce a visual representation of the underlying perceptual structure. In line with this, the first listening test (Step 1) of the experiment was based on the procedure used by Gygi et al.(2007). The group of stimuli for this first step included acoustic and digital wind-like sounds, as well as other sounds (a harmonic sound, an impact sound, and real-world wind sounds) in order to give context to the perceived similarity of the wind effects, and reveal how participants' ratings compared with the original study. Each sound was compared with each other sound, and participants were asked to compare the sounds in pairs and rate how similar they perceived them to be to each other on a 7-point Likert scale ranging from *not similar at all* to *as similar as they could possibly be.*

3.2. Step 2: Connecting Rotation to the Speed of Wind

For a sonic interaction to be *continuous*, the connection between a performance action and resulting sound should be perceptually meaningful. In particular, participants should perceive the resulting sound as the direct result of their own actions. This step of the experiment followed part of the procedure used to evaluate the Spinotron (Lemaitre et al. , 2009), a digital interface created to facilitate a continuous sonic interaction with a digital sound model of a rotating ratchet mechanism through a pumping action. Before using Spinotron in an interactive task, researchers first evaluated participants' ability to perceive variations in the speed of its virtual ratchet sound model. Researchers were able to establish that participants could estimate the rotational speed of the model, measured in RPM, just by listening to its sound. This suggested that participants would be able to understand the connection between the speed of their pumping action and the resulting sound in an interaction with the Spinotron.

The wind machine's crank handle affords a gesture of rotation to the performer, and variations in its rotational speed produce changes in the resulting wind-like sound. This step of the experiment aimed to understand two distinct aspects of this process. First, whether the connection between a rotational movement of a certain speed and the resulting continuous wind-like sound was perceptually meaningful to participants. Secondly, whether the acoustic and digital wind-like sounds could equally communicate variations in the rotational speed of their machine interface to participants. This was important to explore as the final step of the experiment used recordings of both the acoustic and digital wind-like sounds to guide participants to perform with the wind machine interface.

To produce the stimuli for this test, the wind machine interface was performed at different rotational speeds, and the resulting acoustic and digital wind-like sounds simultaneously recorded. Four distinct rotational speeds (0.5RPM, 1RPM, 2RPM and 5RPM) were captured as recorded wind-like sounds. Participants were told that the sounds had been produced by a handle being turned at different speeds, and were asked to rank the acoustic and digital wind-like sounds separately, from slowest to fastest, on a 4-point rating scale from *slowest* to *fastest*.

3.3. Step 3: Interacting with a Continuous Wind-Like Sound

The final step of the experiment focused on operationalising the experience of a continuous sonic interaction with both the acoustic and digital wind-like sounds. This follows prior research in the field of DMI design, where musical performers were given defined cues to imitate, and time to reflect on their performance experiences, when evaluating a new digital musical instrument (Poepel , 2005). The task aimed to establish whether participants perceived their interactions with the acoustic and digital wind-like sounds to be similar to each other, and whether they could perceive a particular rotational gesture of the crank handle in each sound in order to translate it into a performance gesture of their own.

To focus participants' attention clearly on each wind-like sound and how to perform it, recordings of two simple performance gestures (a single rotation, and two rotations at moderate speed) were used as stimuli to elicit their performances. Participants were asked to listen to each sound, and then imitate what they had heard by using the crank handle. To encourage participants to fully explore the expressive range of the acoustic and digital wind-like sounds in performance, they were asked to imitate both the matched source of the sound (e.g. acoustic wind machine imitating an acoustic wind recording) and its counterpart (e.g. acoustic wind machine imitating a digital wind recording). The performances were also recorded for acoustical analysis. Participants were asked to evaluate and describe their own experiences of their performances throughout this step of the experiment, rating their performances for similarity and easiness on 7-point Likert scales. When rating for similarity, participants were presented with a scale from *not similar at all* to *as similar as they could possibly be.* When rating their agreement with the statement *this wind sound is easy to play*, participants were presented with a scale from *strongly disagree* to *strongly agree.* They were also asked to describe each wind sound that they performed by selecting from a list of descriptive words, and give free descriptions of their experiences.

Experimental conditions were controlled as much as possible to make the multimodal feedback consistent across the acoustic and prototype digital wind machine performances. The acoustic wind machine's cloth plays a critical role in the tactile and kinaesthetic experience of its performance, and as such was required to remain in place during a performance of the digital wind-like sound. The acoustic wind machine would therefore constantly produce sound, even during a performance of the digital wind-like sound. To control the sonic experience of participants' performances, the acoustic wind machine was captured with a large diaphragm AKGC414 microphone and delivered via a closed-back pair of Sennheiser HD280 Pro headphones. The live audio from the digital model in Max/MSP was also delivered via the same headphones. The headphones offered up to 32dB of passive noise attenuation, ensuring that participants were isolated from any acoustically produced sound within the room. The efficacy of this setup was confirmed by the first author and also during the pilot study with participants before proceeding to the full experiment. Visual feedback was also controlled in this experimental step in order to focus the interaction purely on the gestural performance of wind afforded by the crank handle. Any sight of the acoustic wind machine's rotating wooden cylinder or moving cloth was removed by concealing its structure behind a cardboard screen, leaving only its crank handle protruding. This eliminated the possibility that the sight of the large wooden structure did not cause participants to make quick assumptions about the weight of the wind machine or the effort required to play it before they had a chance to try it out for themselves.

3.4. Participants

A total of 54 participants were included in the full experiment, giving a statistical power of 0.8 when detecting a large effect size (r = 0.5) at $\alpha \leq 0.05$. However, due to issues with data gathering during testing that would have affected the final analysis, some participants were excluded from each step of the experiment. The exact number of participants retained for each step is reported in the following sections. All manipulations of the experimental data, and the power and significance of each statistical test is also fully reported.

3.5. Apparatus

The experiment took place in an acoustically treated room at the Department of Theatre, Film, Television and Interactive Media, University of York. A MacBook Pro running the Python-based Open Sesame experiment platform (Mathôt et al. , 2012) presented the audio stimuli for each step of the experiment and also collected questionnaire data from participants. The 24bit/48KHz audio clips were played back through an RME Fireface 400 audio interface, and participants listened through a pair of closed-back Sennheiser HD280 Pro headphones.

During the final step, a second laptop was used to run the prototype digital model in Max/MSP, and an additional computer was set up to deliver the sound stimuli and record participants' performances using Avid Pro Tools. Both the Max/MSP patch and the Pro Tools session were obscured from participants to ensure they did not receive any additional visual feedback during their performances. The sound stimuli and live audio of participants' performances was delivered to them via Pro Tools through a closed-back pair of Sennheiser HD280 Pro headphones, which they wore throughout this step of the experiment. Participants' performances in response to the sound stimuli were recorded into the same Pro Tools session. As explained previously, only the crank handle was visible to participants.

4. Stimuli, Procedure and Results for Each Step

4.1. Step 1

The first step of the experiment invited participants to listen to pairs of sounds and rate them in terms of their perceived similarity. This procedure attempted to reveal the perceptual structure of the acoustic and digital wind effects in relation to a real-world wind sound, and whether the prototype digital wind machine produced a wind-like sound perceivably similar to its acoustic counterpart.

4.1.1. Stimuli

The stimuli for this listening test consisted of a total of eight distinct sounds. Field recordings of real-world wind were chosen from the BBC Sound Effects Library (1998) to serve as natural wind stimuli. The acoustic wind machine and prototype digital wind machine were then simultaneously performed by the first author to imitate these natural wind sounds, and the results were recorded. This produced a corpus of wind gestures, each with an acoustic, digital and natural component. Two distinct wind gestures were then chosen from this corpus to serve as stimuli for this listening test. These were designated as *steady* (a consistent, sustained wind sound), and *gusty* (a wind with exaggerated changes in intensity) respectively. To contextualise these wind sounds within a broader perceptual structure of everyday sounds as explored by Gygi et al. (2007), a harmonic sound (a hand-operated horn) (BBC , 1986) and a discrete impact sound (a piece of wood dropping onto a surface) (Hollywood Edge , 1991) were added to the corpus for this listening step.

4.1.2. Note on participants for Step 1

Data from a total of 51 participants was retained from this step of the experiment for the purposes of analysis. All of these participants reported normal hearing. 33 participants identified themselves as female, and 17 identified themselves as male. 40 participants identified themselves as 18-24 years of age, 9 as 25-34, and 2 as 45-54. 38 of the participants reported that they had experience of playing a musical instrument, with 16 designating themselves as beginners, 13 intermediate, and 9 with advanced ability.

4.1.3. Procedure

Sound pairs were created from the corpus of 8 sound stimuli. Each sound was compared to itself and to each other sound, giving a total of 36 pairs of sounds for participants to rate as part of this task. The sound pairs were presented sequentially to participants, with the order of the pairs randomised by the Open Sesame program (Mathôt et al. , 2012). Both components of each sound pair were presented to participants on a single screen in Open Sesame, and could be triggered as many times as required with onscreen buttons. The sounds were not labelled when presented to participants to avoid the use of any terms such as acoustic, digital, continuous or impact, which may have influenced their ratings. Participants were asked to listen to each of the sound pairs and rate the similarity of the two sounds in each pair to each other on a Likert scale from 1 (*not similar at all*) to 7 (*as similar as they can possibly be*), the same scale used by Gygi et al. (2007) in their study of environmental sounds.

An initial practice step asked participants to rate two sound pairs from the corpus, one comparing a sound to itself, and another pair of two distinct sounds, on the similarity scale. Each sound pair was presented only once during the test step, apart from the practice pairs, which were presented again during the main test step. The full trial lasted for approximately 20 minutes.

4.1.4. Results and Analysis

The similarity ratings were scored according to their place on the scale with values from 1 to 7. The overall mean similarity score was 3.77, with an SD of 0.42. The similarity ratings were not normally distributed. This was expected due to the high ratings given to the pairs that compared sounds to themselves. An examination of these scores showed that, while the median similarity of pairs comparing a sound to itself was consistently 7, participants did not always rate these sounds as similar as they could possibly be to each other. Both of the digital wind sounds achieved slightly lower mean similarity scores, but the horn sound achieved the lowest mean similarity score when compared to itself. The scores for these pairs are presented in Table 1 in ascending order of mean similarity, and displayed as a boxplot in Figure 15.

To ensure that the next stage of the analysis of the similarity ratings would produce some robust conclusions for this small group of sound stimuli, participants' individual ratings were adjusted to account for intersubject differences in mean ratings. This process produces a mean similarity rating for each pair of sounds based on an 'agreed' similarity rating scale across the participants, rather than trying to incorporate all of the individual differences in how the decisions on similarity were made. An adjustment factor was calculated for each participant by subtracting the mean similarity of their individual ratings for each pair of sounds from the overall mean simi-

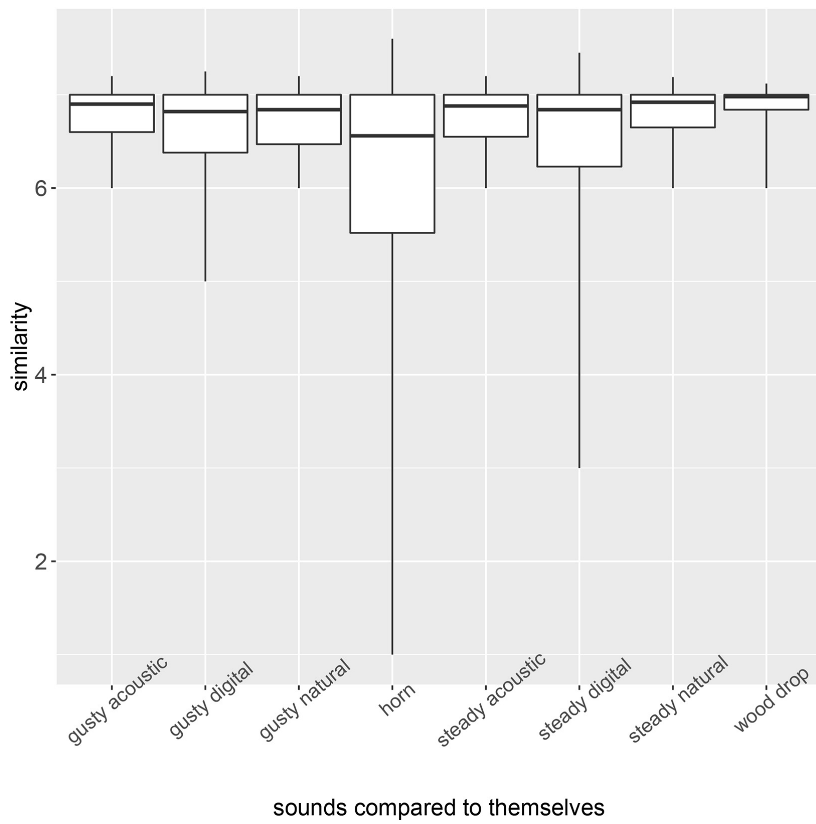

Figure 15: Boxplot representation of the similarity ratings of sounds compared to themselves

Table 1: Similarity ratings of sounds compared to themselves, in order of mean similarity.

Sound compared to itself	Mean similarity	SD	Skewness
Horn	6.57	1.04	-3.74
Gusty Digital Wind	6.82	0.43	-2.33
Steady Digital Wind	6.84	0.61	-5.03
Gusty Natural Wind	6.84	0.36	-1.83
Steady Acoustic Wind	6.88	0.33	-2.30
Gusty Acoustic Wind	6.90	0.3	-2.62
Steady Natural Wind	6.90	0.27	-3.04
Wood Drop	6.98	0.14	-6.73

larity score (3.77). Each participants' ratings were then adjusted by adding their adjustment factor to the rating they had assigned to each pair (Field et al. , 2012). The scores for each same-sound pair were also adjusted to the maximum value of 7. A similarity matrix was then created from the resulting mean similarity scores for each sound pair (Table 2).

A multidimensional scaling (MDS) analysis was performed to express the similarity matrix data as a series of points (one for each sound in the corpus of stimuli) in a two-dimensional space. The similarity matrix was first transformed with the *dist()* function in R into a distance matrix, which expressed the mean similarities between the sounds (Table 2) as Euclidean distances. To discover how many dimensions were required for the MDS procedure, the factoextra package in R (Kassambra & Mundt , 2017) was used to calculate eigenvalues from the distance matrix and express how much variance each factor (or dimension) might account for as a percentage of the

Table 2: Matrix of mean similarity scores produced from participants' similarity ratings. Wind sounds are designated by gesture descriptor and then by source: natural (N), acoustic (A), digital (D).

	Steady N	**Steady A**	**Steady D**	**Gusty N**	**Gusty A**	**Gusty D**	**Horn**	**Wood**
Steady N	*7.0*							
Steady A	5.06	*7.0*						
Steady D	3.98	3.78	*7.0*					
Gusty N	5.06	4.74	3.51	*7.0*				
Gusty A	4.19	5.19	4.04	5.0	*7.0*			
Gusty D	3.21	3.45	5.37	3.51	4.27	*7.0*		
Horn	1.39	1.39	1.74	1.33	1.41	1.15	*7.0*	
Wood	1.09	1.11	1.19	1.15	1.13	1.17	1.35	*7.0*

Table 3: An analysis of variance in the distance matrix produced by the factoextra package in R, showing that 95.3% of the variance in the data can be accounted for by the first three dimensions.

Dimension	1	2	3	4	5	6	7	8
% Variance	74.6%	12.5%	8.2%	2.1%	1.3%	0.8%	0.6%	0%

total variance (Table 3). The results showed that most of the variance in the distance matrix (95.3% in total) could be accounted for with the first three factors, meaning that three dimensions would be appropriate for the final MDS analysis. This result is confirmed by Gygi et al.'s study (2007), which proposed a three-dimensional solution as most appropriate for evaluating a wider variety of environmental sounds.

An MDS analysis using the simplest CLASCAL method was then performed on the distance matrix using three dimensions and the *cmdscale* function in R. This produced coordinates for the sound stimuli along each of the

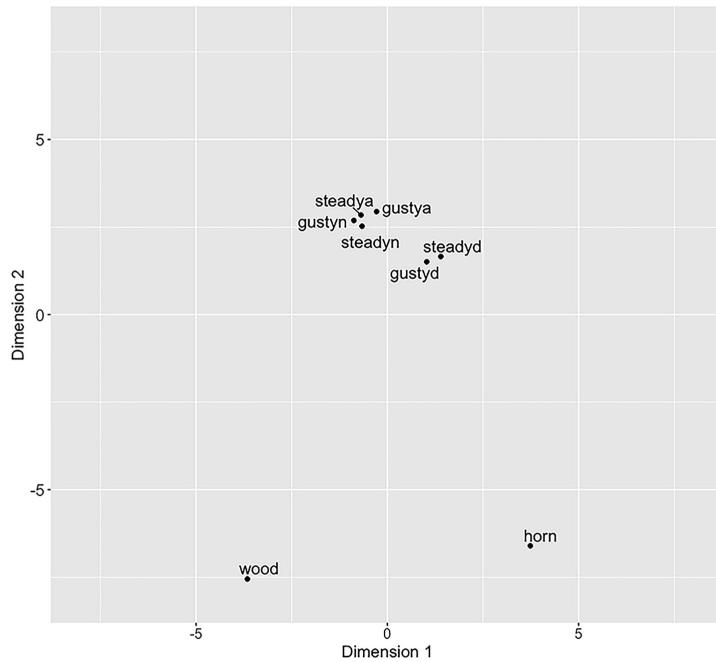

Figure 16: Two-dimensional plot of the MDS solution for Dimension 1 against Dimension 2.

three dimensions. Dimensions 1 and 2 were rotated before producing the final two-dimensional plots to position the points in a manner consistent with the MDS analysis produced in Gygi et al. (2007), which positioned continuous sounds in a distinct cluster in the centre and towards the top of the y-axis (Figure 16).

The resulting plot of Dimensions 1 and 2 cluster the sound stimuli into three distinct groups – continuous sounds (winds), harmonic sounds (horn) and discrete impacts (wood). Within the continuous sound cluster, the digital winds sounds are closer to each other than to the acoustic and natural winds. The acoustic wind sounds are very close to the natural wind sounds. Dimension 1 was also plotted against Dimension 3 (Figure 17).

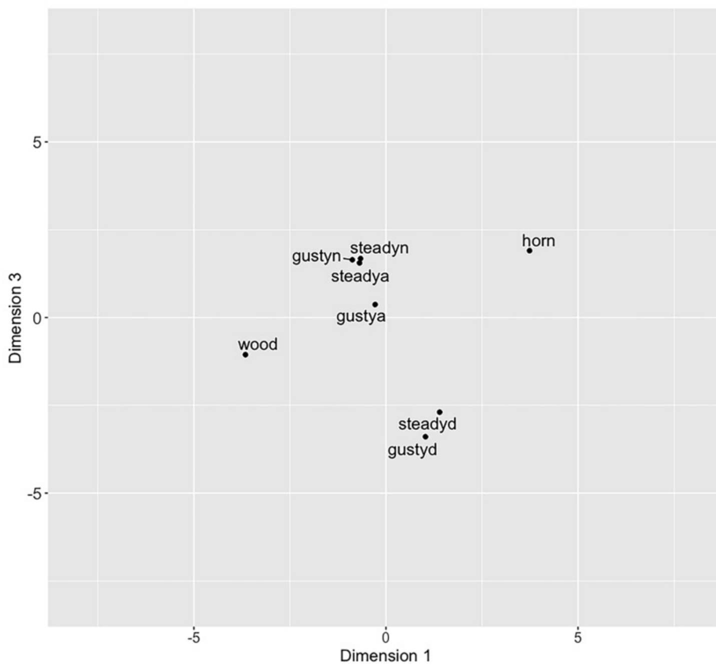

Figure 17: Two-dimensional plot of the MDS solution for Dimension 1 against Dimension 3.

The plot of Dimension 1 against Dimension 3 shows the horn and wood sounds further apart from each other, with the continuous wind sounds again clustered together. The acoustic wind sound is closer to the natural wind sound here, particularly its steady gesture. The digital wind sounds are further removed from the other wind sounds in this configuration.

A hierarchical cluster dendrogram (Figure 18) was also produced from the distance matrix to make the groupings more explicit. This shows that the horn and wood sounds are very distinct from the cluster of continuous sounds. Within the continuous sounds, each source of the wind (natural, acoustic or digital) is responsible for the grouping rather than the gestures themselves (steady or gusty), but the acoustic and natural wind sounds are grouped much more closely together while the digital wind sounds are in their own distinct part of the continuous cluster.

In order to discover which acoustical qualities of the sound stimuli could be influencing their perceived similarity to each other, their acoustic features were correlated with their coordinates along the dimensions of the MDS solution. Due to the time limitations of this study as one step of the full experiment, there are only a limited number of observations available for this analysis (8 points along each dimension, one for each sound), and so these results should be considered with caution. However, given that the MDS analysis has produced results that confirm the clusters observed in the larger study by Gygi et al. (2007), it is reasonable to produce some observations that could be confirmed with a further in-depth study to evaluate a larger group of sound stimuli. To examine the potential acoustic factors in the results of this listening test, the sound stimuli were acoustically eval-

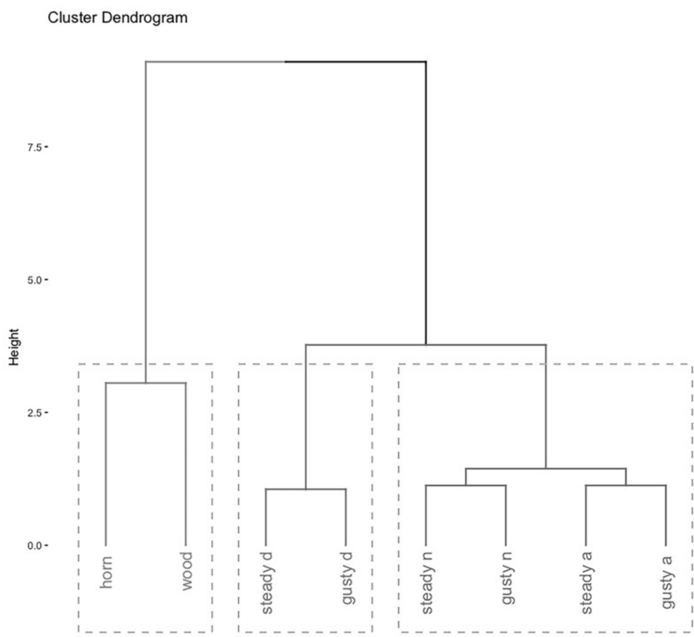

Figure 18: Hierarchical clustering of the distance matrix data.

Table 4: Table of correlations (Spearman's rho) between the three dimensions of the MDS analysis and the acoustic features of the sound stimuli [$p \leq .001 = ***$, $p \leq .01 = **$, $p \leq .05 = *$]

Acoustic Feature	**Dim. 1 (74.6%)**	**Dim. 2 (12.5%)**	**Dim. 3 (8.2%)**
Brightness	-0.71***	*0.06*	0.65*
Inharmonicity	-0.90***	0.67*	*0.44*
Centroid	-0.86***	0.64*	0.64*
Spread	-0.77**	0.66*	0.68*
Skewness	0.76**	-0.80**	-0.71**
Event Density	*0*	0.62*	*-0.22*

uated using the MIR Toolbox in Matlab (Lartillot & Toiviainen , 2007) to produce some numerical measures of their acoustic features. This data was then correlated with the coordinates extracted from each dimension using a Spearman's rho coefficient, as there were a small number of coordinates and they were not normally distributed. The results are shown in Table 4.

The correlations show that Dimension 1 seems to be associated highly with spectral measurements of the sounds, including statistical measures of the spectrum, which reflects the results from the more extensive study by Gygi et al. (2007). This suggests that the spectral content or timbral qualities of the sound stimuli were responsible for 74.6% of the variance in the ratings of the stimuli in this study. In particular, the noisiness of the sounds (inharmonicity) and the energy of their spectra (centroid) seem to have been particularly important.

Dimension 2, accounting for 12.5% of the variance in the similarity ratings, shares an association with statistical measures of the spectrum, in particular whether the frequency content of the sounds was clustered towards the low or high frequencies (skewness). It is also singularly associated with the frequency of onsets in the amplitude envelope of the sounds (event density). These associations also reflect the results of the more extensive study by Gygi et al. (2007).

Dimension 3 is most highly associated with the spectral skewness of the stimuli and is not associated with either noisiness or the amplitude envelope of the sounds. It accounts for a further 8.2% of the variance in the similarity ratings for this study. These associations with spectral features of the sounds reflect the results in the more extensive study by Gygi et al. (2007).

4.1.5. Summary of Findings

Participants clustered all of the wind-like sounds together in a group of continuous sounds, but rated the acoustic wind much more similar to its natural than its digital counterpart. The results therefore did not allow the null hypothesis to be rejected (H1-0).

4.2. Step 2

The second step of the experiment aimed to evaluate both whether participants could perceive different levels of rotational speed from the resulting sounds of the two wind machines, and also whether those differences in rotational speed could be communicated equally by both the acoustic and digital wind-like sounds. Rotational speed was measured in RPM and calculated in MaxMSP from the data stream of the rotary encoder coupled to the acoustic wind machine. RPM measurements were displayed visually in MaxMSP, allowing speed to be monitored during the creation of stimuli for this step of the experiment. The procedure was devised following the listening experiment outlined in Lemaitre et al. (2009).

4.2.1. Stimuli

The relatively slow and restricted range of RPM afforded by the acoustic wind machine interface produced a limited corpus of sounds at unequal speed intervals. As such, the task was designed to require participants to rank the sounds they heard in order of speed, rather than estimate their speed on a continuous scale. A corpus of eight audio clips of the acoustic and digital wind-like sounds resulting from rotational speeds of 0.5RPM, 1RPM, 2RPM and 5RPM was produced. The sounds were produced by partial rotations of the crank handle in order to ensure a consistency of speed for the full duration of each clip, and speed of rotation was monitored in RPM in Max/MSP during recording. Following the procedure in Lemaitre et al. (2009), all of the audio clips were of a similar duration, in this case a maximum of two seconds in length.

4.2.2. Note on Subjects for Step 2

All of the participants who had previous participated in the similarity ratings step also participated in this step of the experiment. However, incomplete data from 5 participants had to be eliminated from the analysis. This brought the total to 46 participants for this listening test: 31 identified as female and 15 identified as male. 36 participants identified themselves as 18-24 years of age, 8 as 25-34 years of age, and 2 as 45-54 years of age. 33 of the participants reported that they had experience playing a musical instrument, with 15 of these designating themselves as beginners, 10 as intermediate and 8 as advanced. All participants reported normal hearing.

4.2.3. Procedure

The acoustic and digital wind-like sounds were presented to participants separately to be ranked in order of their perceived rotational speed. This listening step was based on a repeated measures design, with all participants ranking both the acoustic and the digital wind-like sounds. The order of presentation of the stimuli was randomised, with 23 participants rating the group of acoustic sounds first and 23 rating the group of digital sounds first in order to minimise order effects. The order of the four sounds for each task were randomised in Open Sesame (Mathôt et al. , 2012) and labelled as *sound 1*, *sound 2*, *sound 3*, and *sound 4*. Each sound could be triggered with an onscreen button.

Participants were told that each of the four sounds had been made by a handle being turned at different speeds. They were asked to listen to each sound, play them as many times as they liked, and then rank the sounds in terms of the speed of the turning handle on a scale from 1(*slowest*) to 4(*fastest*). Participants were only given one opportunity to rate each kind of sound for perceived rotational speed. Once the participants had finished rating the first group of sounds (e.g. acoustic), they then proceeded to the second group of sounds (e.g. digital) and rated them.

4.2.4. Results and Analysis

The speed ratings were scored with values from 1 to 4 according to their ranking on the scale. The speed ratings for both the acoustic and digital

Table 5: A comparison of descriptive statistics for the perceived speed of the sounds as ranked by participants.

RPM	Expected Rank	Sound	Mean	SD	Median
0.5	1	*Acoustic*	1.83	1.0	1
		Digital	2.0	1.19	1
1	2	*Acoustic*	3.17	0.9	3
		Digital	2.76	1.02	3
2	3	*Acoustic*	2.33	1.09	2
		Digital	2.76	1.14	3
5	4	*Acoustic*	2.65	0.99	3
		Digital	2.61	0.95	3

sounds were not normally distributed. An examination of the mean and median speed ratings showed that participants did not consistently rank the sounds in order of the rotational speed that produced them. The mean ratings for the acoustic wind machine sounds showed more variation than those for the digital wind machine sounds, which were grouped closely together (Table 5).

Plotting the actual rotational speeds of the corpus of sounds against the speed rankings by participants shows that, despite the different rotational speeds, each sound's rankings were spread over a range, and not focused on one particular rank (Figure 19).

A Friedman rank sum test was performed to establish whether the rankings given to each sound differed significantly from each other. This showed that there were statistically significant differences in the way that partic-

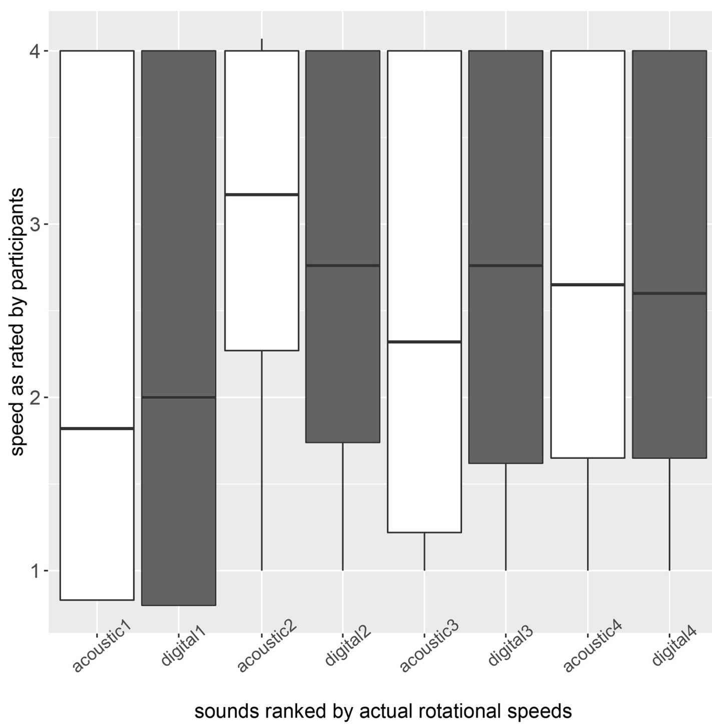

Figure 19: Boxplot of the speed rankings of the acoustic and digital wind sounds for each actual speed (0.5RMP, 1RMP, 2RPM, 5RMP).

Table 6: Results of the statistical testing to compare how the wind-like sounds were ranked in order of speed.

Test: Friedman's ANOVA	**Significance**	**Effect Size**
2(7) = 44.194, Z = -5.2	p <0.01	1.16 (large) statistical power = 0.8
Post-hoc comparisons: Wilcoxon signed rank test	**Significance**	**Effect Size**
Acoustic 1 (0.5RPM) – Acoustic 2 (1RPM): Z = -4.13	p <0.01	-0.71 (large) statistical power = 0.8
Acoustic 1 (0.5RPM) – Acoustic 4 (5 RPM): Z = -1.95	p = 0.05	-0.46 (medium) statistical power = 0.8
Acoustic 1 (0.5RPM) – Digital 2 (1RPM): Z = -3.24	p <0.01	-0.60 (large) statistical power = 0.8
Acoustic 2 (1RPM) – Digital 1 (0.5RPM): Z = -3.89	p <0.01	-0.68 (large) statistical power = 0.8

ipants had ranked the various sounds. Post-hoc testing using a Wilcoxon signed-rank test with a Bonferroni correction applied showed that only some of the rankings differed significantly from each other (Table 6).

4.2.5. Summary of Findings

Participants did not consistently rank the sounds they heard in the order of the rotational speed of the crank handle that produced them, and so did not allow the first null hypothesis (H2a-0) to be rejected.

However, statistical testing of the speed rankings did indicate that there were some statistically significant differences in how participants ranked the acoustic wind-like sounds for speed. Statistically significant differences were also observed between the rankings for the acoustic wind-like sound and the digital wind-like sound when produced with rotational gestures at 0.5RPM and 1RPM, and 1RPM and 0.5RPM respectively. No statistically significant differences were observed when comparing the rankings between the various digital wind-like sounds. This suggests that the two wind-like sounds are not able to communicate their speed equally, and so the results did not allow the second null hypothesis to be rejected (H2b-0).

4.3. Step 3

The final step of the experiment attempted to compare how participants experienced a continuous sonic interaction with the acoustic and digital wind-like sounds. This interaction was facilitated by the acoustic wind machine interface, maintaining a continuity of tactile and kinaesthetic feedback across both performances. The procedure was devised from previous work undertaken to evaluate DMIs (Poepel , 2005). Participants were given defined sonic cues to imitate with each wind-like sound, followed by time to reflect on their performance experiences. The detailed procedure and results of this step have been reported previously (Keenan, F., & Pauletto, S. , 2019), but are summarised here to facilitate a full discussion of all results from the study.

4.3.1. Stimuli

Two simple rotational gestures were chosen to serve as stimuli for participants' performances; a slow, single rotation, and two rotations performed at a moderate and steady speed. These gestures were recorded for both the acoustic and digital wind-like sounds. Another recording of a natural wind sound consisting of several short gusts of varying speed was chosen from the

BBC Sound Effects Library (1998) for use in the practice step.

4.3.2. Note on participants for Step 3

The evaluation was undertaken with 48 participants who had first participated in the previous two listening steps. Of these, 32 identified themselves as female and 16 as male. 38 participants designated themselves as 18-24, 8 as 25-34, and 2 as 45-54 years old. 13 participants said they did not have experience of playing a musical instrument, 15 played a musical instrument at beginner level, 12 at intermediate level and 8 at advanced level. All participants reported normal hearing.

4.3.3. Procedure

The evaluation was based on a repeated measures design, with all participants performing with both the acoustic and digital wind-like sounds in response to all of the stimuli. To avoid order effects, the order of presentation of the acoustic and digital wind-like sounds and sound stimuli were randomised. This created four distinct groups of twelve participants.

Participants were shown the crank handle and advised that they would be able to perform a wind sound by rotating it. They were told that there would be two wind sounds to perform with during this evaluation, and that they would get to perform with both of these sounds, one after the other. No terms such as *acoustic* or *digital* were used to ensure that participants' responses would not be influenced. Participants were then asked to listen to a wind stimulus played through their headphones, and then try to imitate what they had heard directly afterwards by turning the crank handle. There was a practice step, and then a test step, for both the acoustic and digital wind-like sounds. During each practice step, participants imitated the natural wind sound (BBC , 1998) and answered all of the questions that would be presented during the test step.

Participants were presented with a range of test questions to evaluate their experiences. They were first asked to rate how similar they perceived their own performances to be to the stimuli on a scale of 1(*not similar at all*) to 7(*as similar as they can possibly be*). Participants were then asked to rate how far they agreed with the statement *'This wind sound is easy to play'* on a scale of 1(*strongly disagree*) to 7(*strongly agree*). Next, a list of possible descriptors for the wind-like sound that had been performed was presented, and participants were asked to describe the wind sound they had just played by selecting from these. There was also a space to add a descriptor of their own to this list. Finally, participants were given the opportunity to provide some free description of their experiences of playing each of the wind-like sounds.

4.3.4. Results and Analysis

Participants' ratings of perceived similarity between the sound stimuli and the wind-like sounds they had performed to imitate them were scored with values from 1 to 7. A summary of the similarity ratings showed that the acoustic wind machine performances had a higher mean rating for similarity to the stimuli presented (4.88, with an SD of 1.66) than the prototype digital wind machine performances (2.77, with an SD of 1.51). Statistical testing confirmed that there was a significant difference between the ratings given to the acoustic wind machine performances and the performances with its digital counterpart (Table 7).

Table 7: Results of the statistical testing of participants' similarity ratings.

Test: Wilcoxon Signed Rank	**Significance**	**Effect Size**
Z = -5.40	p <0.01	-0.78 (large) statistical power = 0.8

Table 8: Results of the statistical testing of participants' easiness ratings.

Test: Wilcoxon Signed Rank	**Significance**	**Effect Size**
Z = -5.62	p <0.01	-0.81 (large) statistical power = 0.8

Participants' scores for their responses to the statement *'The wind sound is easy to play'* were scored with values from 1 to 7. A summary of the easiness ratings showed that the acoustic wind machine had a higher mean rating for ease of play (4.98, with an SD of 1.19) than the prototype digital wind machine (3.04, with an SD of 1.41) . Statistical testing confirmed a significant difference between how easy the acoustic and digital wind-like sounds were perceived to play (Table 8).

Participants were invited to describe the acoustic and digital wind-like sounds by choosing as many descriptors as they liked from a list. These descriptors were associated with a range of categories, including weather, force, and onomatopoeic descriptions of wind. Responses were collated to produce a bar graph in R comparing the frequency of the descriptors given to each wind machine (Figure 20).

This showed that the most popular descriptor for both the acoustic and digital wind-like sounds was the action-oriented *swishing*, followed by the force descriptor *strong* and the weather-associated *gusty*. The acoustic wind-

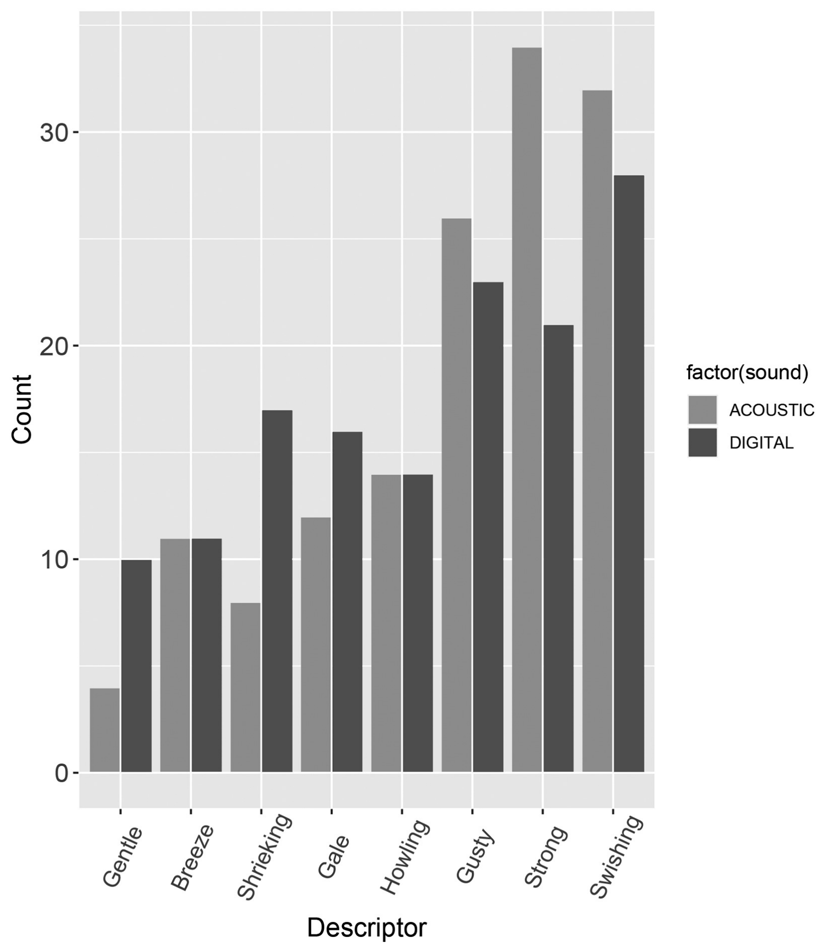

Figure 20: Summary of the descriptors participants assigned to their performances of the acoustic and digital wind-like sounds.

like sound scored more highly across these three descriptors than its digital counterpart. The digital wind-like sound was described with a fuller spread of adjectives and was described more often as *shrieking* and *gale* when compared with its acoustic counterpart.

The free descriptions participants gave of their experiences of performing with the acoustic and digital wind-like sounds were collated and coded. It was evident that participants had acquired some vocabulary from the list of descriptive words previously presented to them, as words like *gentle*, *strong* or *gusty* were included within their free descriptions. Some interesting issues and trends emerged. Participants readily connected the speed of rotation of the handle with what they variously described as the *speed*, *motion*, *rhythm* or *pace* of the resulting wind-like sound, whether it was acoustic or digital in origin. Some participants reported that the crank handle felt heavier to turn when performing the acoustic wind-like sound.

The evaluation produced a corpus of recordings of participants' performances of the acoustic and digital wind-like sounds in response to both the acoustic and digital stimuli. These recordings were exported from Pro Tools as audio clips and analysed in Matlab using the MIR Toolbox (Lartillot & Toiviainen , 2007) to produce numerical measures of the spectrum (brightness, inharmonicity, spectral centroid, spread and skewness) and amplitude envelope (event density - a measure of the frequency of onsets). The resulting numerical values for each feature were then collated together for statistical analysis in R.

To establish whether the source of the stimulus presented to participants (acoustic or digital) might have influenced their performances, gestures per-

Table 9: Results of the statistical testing to compare the acoustic analyses of participants' recorded performances.

Test: Wilcoxon Signed Rank	Significance	Effect Size
Acoustic Wind Event Density (1 rotation) Z = -3.46	p <0.01	-0.49 (medium) statistical power = 0.8
Digital Wind Event Density (1 rotation) Z = -2.14	p <0.05	0.3 (medium) statistical power = 0.8

formed with the same system were paired in order to facilitate their statistical comparison. For example, two rotations performed with the acoustic wind machine in response to an acoustic stimulus were compared to two rotations performed with the acoustic wind machine in response to a digital stimulus. Statistical testing compared each acoustic feature of the paired gestures. This testing established no statistically significant difference across the spectral measurements of the performances. For the measures of event density, no statistically significant difference was found between the paired gestures of two steady rotations. However, statistically significant differences were found for measures of event density for a single rotation performed with both the acoustic wind machine and the prototype digital wind machine (Table 9).

This suggests that the gesture of two rotations performed with the acoustic and digital wind-like sound was quite consistent regardless of whether participants had first listened to a stimulus that matched the sound that they were performing. For a single rotation, performances seem to have been more directly influenced by whether the stimulus presented matched the sound of the wind machine being played.

4.3.5. Summary of Findings

The results of this step established that, while the continuous sonic feedback was the only kind of multimodal feedback that changed between these two performance conditions, participants found the acoustic wind machine significantly easier to play and perceived it as sonically similar to the stimuli used to elicit their performances. By contrast, the digital wind-like sound was rated as significantly less easy to play, and participants found their performances with it to be significantly less similar to the stimuli they were trying to imitate. Statistical testing showed that the ratings for similarity and ease of play were significantly different depending on the kind of wind-like sound being rated, and so the results did not allow the null hypothesis to be rejected (H3-0). These results suggest that the digital model of the acoustic wind machine needs to be developed further. Some interesting information emerged from participants' free description of their performances, in particular that the change in sonic feedback from an acoustic to digital sound might have influenced how the physical properties of the acoustic wind machine were experienced.

Acoustical analysis of participants' recorded performances established that there was no statistically significant difference in the acoustical measurements of sounds performed in response to a stimulus that matched the wind-like sound being played when compared with performances responding to an unmatched stimulus. The exception to this finding was the measurement of event density, or number of onsets in the sound's amplitude envelope per second, which was found to be significantly different for a single rotation performed with the acoustic wind machine between the acoustic and digital wind stimuli. The same pattern was visible for a single rotation with the digital wind-like sound.

5. Discussion

5.1. Experiment Design

We propose that the methods pursued for this study have proven effective in evaluating the perceptual qualities and enactive potential of a theatre sound effect design, and should be expanded upon. This study has established a baseline of findings that can be explored with the development of the experimental steps into dedicated experiments. In particular, a larger corpus of sounds for the listening tests would improve the sensitivity of the statistical analyses presented here. This would reflect more individual differences in the similarity ratings and help to establish which of the acoustic features of the stimuli predicted their ordering along each dimension of the MDS result, and also facilitate a more conclusive analysis of whether the actual RPM that produced a wind-like sound might predict how participants rank it for speed.

Adjustments to a future experiment design may also improve upon the quality of data captured. The order in which the tasks were presented may have been a factor here, for example. Placing the second listening step after the performance step might have usefully built upon participants' new familiarity with the wind-like sounds. In the performance step (Step 3), when freely describing their performance experiences, some participants used the vocabulary of descriptors they had been previously asked to choose from. Future experiment designs could ensure that participants are not primed before their free descriptions are solicited. A future study could also elicit participants' classifications of what they perceive to be the material source of the acoustic and digital wind-like sounds, particularly in advance of ranking the sounds in order of speed. In the evaluation of Spinotron, researchers showed that perceptions of what kind of material caused the sound may have influenced participants' understanding of the speed of the digital ratchet model (Lemaitre et al. , 2009).

5.2. Wind-Like Sounds and Sonic Affordances

The results of the two listening steps suggest that, although the theatre wind machine design couples a rotational performance gesture to a wind-like sound, this gesture is not immediately perceivable from the resulting sound when heard as recorded audio. This suggests that the sound of wind might not present a clear sonic affordance (Altavilla et al. , 2013) to a listener. The analysis of the similarity ratings from the first listening step suggests that the most important factor in participants' perception of the sounds was their timbre rather than their gesture (*steady* or *gusty*), chiming with the previous research by Gygi et al.(Gygi et al. , 2007) on which this procedure was closely based.

Similarly, the second step of the experiment showed that participants did not perceive clear differences between different rotational speeds of the crank handle when presented with the acoustic and digital wind-like sounds that they produced. This casts doubt on whether *rotation* can be perceptually understood as performative action that directly produced a recorded wind-like, or in the case of the partial rotations used here - *scraping*, sound. The continuous nature of the sound stimuli, and the lack of a reference sound to establish a perceptual notion of speed, may have also been a factor here. The evaluation of the Spinotron's sound (Lemaitre et al. , 2009), on which this procedure was based, focused on a ratchet model consisting of many impacts being triggered one after another, which may have provided a more reliable reference for participants as to the speed of movement.

These findings raise potentially interesting questions about the nature of continuous sonic interactivity, and whether truly continuous sounds like the wind effect investigated here can produce meaningful interactions without an innate perceptual link to a specific performance action.

5.3. Bodily Skill in Wind Performance

The easiness ratings and free descriptions offered by participants in the third step of the experiment suggested that they perceived their performances with the acoustic wind machine's crank handle as intimately linked to the resulting wind-like sound. So, while the wind-like sounds did not suggest a specific action or gesture to participants during the two listening steps, they somehow understood how their rotation action linked to that sound in performance. A potential reason for this was revealed by the analysis of the recordings produced from participants' performances. A statistically significant difference was found between the frequency of onsets in the amplitude envelopes of the single rotations for both the acoustic and digital wind-like sounds. While this might suggest that participants played the wind machines quite differently depending on the kind of wind stimulus (acoustic or digital) presented to them to elicit their performance, this difference was not also evident in the gestures of two steady rotations. It is possible that participants understood the stimuli of two steady rotations much more easily, but given the lower ratings for similarity and easiness participants gave to the digital wind-like sound, it is unlikely that the digital stimuli were so simple to imitate.

It is proposed that this continuity of gestural response evidenced in the performances of two steady rotations may be the result of the mechanical qualities of the acoustic wind machine itself, rather than the responses of participants. With a single rotation, the acoustic wind machine's cylinder may not have time to accumulate rotational energy and push forward from the movement of the performer's hand on the crank handle. However, with a gesture of two rotations, the moving cylinder must be imposing more of its flywheel qualities, and hence some regularity, on the performer's rotational movement. The *feel* of this rotational inertial may be a critical factor in how the rotation action of the crank handle perceivably corresponds with the continuous wind-like sound, allowing the performer to enactively learn how to use the wind machine.

The importance of this perceivable continuum of energy (Cadoz , 2009) was also highlighted by participants' free descriptions, which suggested that despite the continuity of feedback across the two interactions, the digital wind-like sound may have nevertheless influenced participants' tactile and kinaesthetic experience of the wind machine interface itself. This potential connection with previous research on the influence of sonic feedback on haptic or movement perception (DiFranco et al. (1997), Avanzini & Crosato (2006), Turchet et al. (2013) and Kang et al. (2021)) has not been explored as part of this research and should be examined further.

5.4. Development of the Prototype Digital Wind Machine

Drawing these findings together highlights some particular areas for improvement of the digital model in Max/MSP. The MDS solution along Dimension 1 (Figure 13) indicates that perhaps the whistling Aeolian tone of the acoustic wind has been overemphasised within the digital wind-like sound. The speed rankings given to the digital wind-like sound in the second listening step were not consistent with those of the acoustic wind-like sound, suggesting that further improvements to the timbre produced by the digital model may bring these results closer to that of its acoustic counterpart. The ratings and free descriptions given for the digital wind-like sound performances during the final step of the experiment may reflect the need to improve the model's response to variations in performance gesture. Despite its crank handle and wooden interface being used to drive the digital model, the role of dynamics (Menzies (2002) and Leonard et al. (2020)) in the acoustic wind machine's sound production have not been fully accounted for digitally. The key to achieving an improved response to variations in performance gesture may lie in the development of a rotational inertial model within the program in Max/MSP, thereby mapping the progress of the digital wind-like sound to a similar accumulation of energy that resists changes in rotational speed. Any development of the digital wind-like sound can then be re-evaluated against the findings of this study.

6. Conclusion

Both sound and performance action, material interaction and effect, the wind machine design is firmly between the clear categories that often characterise experimental evaluation of sound and perception or interface interaction. Using historical theatre sound effect designs as the focus of an evaluation like this allows participants' perceptual experiences of incrementally different modes of feedback, in a continuous sonic interaction, to be explored in detail.

For instance, this evaluation of the acoustic wind machine and its digital counterpart in performance has confirmed that the sonic response of the digital model could benefit from being calibrated further. However, the acoustic wind machine was itself rated highly for ease of performance and similarity to the stimuli it imitated, confirming its enactive qualities. The potential of the mechanical wooden interface playing a role in facilitating a meaningful link between a performer's action and the complex wind-like sound is interesting, as the flywheel properties of the cylinder and axle design may have a critical role in enhancing the enactive potential of this particular theatre sound effect design. Isolating the sonic feedback as part of this evaluation has also shown that despite the continuity of tactile and kinaesthetic feedback across the interactions, participants perceived their acoustic and digital performances significantly differently.

How far the digital model needs to be developed in order to capture more of the enactive experience of the acoustic wind machine in performance should continue to be investigated to help to further develop the potential of digital systems to afford rich, intuitive encounters with performable everyday sounds.

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Data Availability

The data gathered in the course of this evaluation is available from the authors via http://etheses.whiterose.ac.uk/24057/.

Conflict of interest

The authors declare that they have no conflict of interest.

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