Data Driven Analysis of Tiny Touchscreen Performance with MicroJam

Charles P Martin[1,2,3] and Jim Torresen[2,3]

[1]Research School of Computer Science, Australian National University
[2]Department of Informatics, University of Oslo
[3]RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion, University of Oslo

May 2020

Abstract

The widespread adoption of mobile devices, such as smartphones and tablets, has made touchscreens a common interface for musical performance. While new mobile music instrument have been investigated from design and user experience perspectives, there is little examination of the performers' musical outputs. In this work, we introduce a constrained touchscreen performance app, MicroJam, designed to enable collaboration between performers, and engage in a data-driven analysis of more than 1600 performances using the app. MicroJam constrains performances to five seconds, and emphasises frequent and casual music making through a social media-inspired interface. Performers collaborate by replying to performances, adding new musical layers that are played back at the same time. Our analysis shows that users tend to focus on the centre and diagonals of the touchscreen area, and tend to swirl or swipe rather than tap. We also observe that while long swipes dominate the visual appearance of performances, the majority of interactions are short with limited expressive possibilities. Our findings enhance our understanding of how users perform in touchscreen apps and could be applied in future app designs for social musical interaction.

1 Introduction

Popular social media apps for mobile devices have allowed millions of users to engage with creative production of images and text. These devices' cameras,

Citation: Martin C. P. & Torresen J. (2020). Data-Driven Analysis of Tiny Touchscreen Performance with MicroJam. *Computer Music Journal*, *43*(4), 41-57.
DOI:10.1162/comj_a_00536

touchscreens, powerful processors, and portability suggest on-the-go creativity, and it would appear that straightforward sharing with friends, or a wider network of followers, is a key factor in encouraging users to create content of all forms. Given the many affordances of mobile devices, it has been well-noted that they are suitable platforms for music making (Tanaka 2010). Many creative mobile music apps have appeared in recent years, for example: Magic Fiddle (Wang et al. 2011); Ocarina (Wang 2014); Orphion (Trump and Bullock 2014); PhaseRings (Martin et al. 2016); and TC-11 (Schlei 2012). Despite interest in these apps, mobile musical creation has not yet been adopted as an integrated element of mainstream social media, although some music apps have provided social features. Furthermore, few musical apps have attempted to emphasise ensemble, rather than individual, performance, even though group music-making is often seen as a valuable social activity.

In this article, we present the design for *MicroJam*, a collaborative and social mobile music-making app, and an analysis of more than 1600 touchscreen performances that have been created so far. The design of MicroJam emphasises casual, frequent, and social performance. As shown in Figure 1, the app features a very simple touchscreen interface for making electronic music where skill is not a necessary prerequisite for interaction. MicroJam departs from other touchscreen instruments by imposing limits on the musical compositions that are possible; most importantly, performances are limited to five seconds in length. These "tiny" performances are uploaded automatically to encourage improvisation and creation rather than editing. Users can reply to others' performances by recording a new layer, this combines social interaction with ensemble music making.

In the sections that follow, we motivate MicroJam's design with a discussion of music-making in social media, and the possibilities for asynchronous and distributed collaborations with mobile musical interfaces. We describe the app's design and the interactive music mappings of the nine synthesised instruments that are made available in its interface. We also formalise the concept of "tiny" touchscreen performances. The main contribution of this work is in our analysis of a dataset of more than 1600 tiny performances saved on the app's cloud database by testers and users. We consider this dataset from several levels of abstraction: individual touchscreen interaction events, aggregated touchscreen gestures, and whole performances. This analysis allows us to draw conclusions about how these users perform in MicroJam, and to characterise the musical behaviour in the tiny performance format. While our app design draws on themes introduced by other authors, this is the first time that a systematic and data-driven analysis of a large dataset of touchscreen performances has been published for such a system. Our findings, as well as our data-driven method, could be applied to the design and study

Figure 1: MicroJam allows users to create short touchscreen performances that are shared to other users. Replies to performances form distributed and asynchronous duets. A video demo of MicroJam is available online:`https://doi.org/10.5281/zenodo.797119`

of other touchscreen music apps and other types of interactive music systems as well as future revisions of MicroJam.

This article is a revised and extended version of a previous conference paper (Martin and Torresen 2017), in this new research, we present the fully developed app and an analysis of touchscreen performances.

2 Background

Commodity mobile devices such as smartphones and tablets have often been reframed as musical instruments for research, artistic exploration, and entertainment, forming the field of mobile music (Gaye et al. 2006). The sensors and multitouch screens of smartphones provide many affordances for new kinds of musical software (Essl and Rohs 2009; Tanaka 2010) and the ubiquity of these devices increases the possibility of musical participation by a wide audience (Essl and Lee 2018). Most mobile music apps have used the touchscreen as an expressive musical controller. Some apps, such as Magic Fiddle (Wang et al. 2011) imitate existing musical instrument, but others, such as Crackle (Reus 2011), or TC-11 (Schlei 2012), have defined new ways to connect interaction on the touchscreen to sound synthesis algorithms.

While the design and evaluation of mobile music apps have been reported in the academic literature (see, e.g., Essl and Lee (2018); John (2013); Gaye et al. (2006) for surveys), few analyses exist of the *music* created with these systems. Evaluations of these systems tend to focus on either the design and gesture-to-sound mappings (e.g., d'Alessandro et al. (2012)), or on the experience of the musicians using the apps (e.g., Martin et al. (2016)). It has previously been argued that archives of touchscreen control data can go beyond audio in terms of analysis of tablet musical performances (Martin and Gardner 2016). Smith (2013) analysed a database of 800,000 MIDI performances of popular songs played in the Magic Piano tablet app and identified musical behaviours based on geographical location of the performer. Similar data from motion capture systems has previously been used as a basis for analysis of human interactions between movement and sound (Kelkar and Jensenius 2018). In this work, we perform an analysis on mobile app touchscreen data to understand how users interact musically with MicroJam.

2.1 Social Music-Making and Constraints

Many social media platforms emphasise the value of constrained contributions by users. Twitter famously limited written notes to 140 characters (Gligorić et al. 2018), Instagram constrained images to square format, and the (now defunct) Vine platform only allowed six second micro-videos (Redi et al. 2014). Constraints are often thought to lead to increased variability and creativity in the arts (Stokes 2008) and in electronic musical instruments (Gurevich et al. 2012). Posts in Twitter or Instagram are intended to be frequent, casual, and ephemeral, and it could be that these constrained formats have helped these apps to attract millions of users and encourage their creativity in the written word or photography. While social media is often used to promote music (Dewan and Ramaprasad 2014), music *making* has yet to become an important creative part of the social media landscape outside of a number of standalone apps.

While music is often seen as an activity where accomplishment takes practice and concerted effort, casual musical experiences are well-known to be valuable. Accessible music making, such as percussion drum circles, can be used for music therapy (Scheffel and Matney 2014). Augmented reality instruments (Correa et al. 2009) and touchscreen instruments (Favilla and Pedell 2013) have also been used for therapeutic and casual music-making. Apps such as *Ocarina* (Wang 2014) and *Pyxis Minor* (Barraclough et al. 2015) have shown that simple touchscreen interfaces can be successful for exploration by novice users as well as supporting sophisticated expressions by practised performers.

2.2 Collaboration in Mobile Music

Telecommunication networks have long been used to facilitate and democratise musical collaboration (Kim-Boyle 2009); for example, Neuhaus' *Radio Net* (1977) used the sounds of radio listeners collectively calling in and whistling into their phone. Later, computer networks enabled software instruments to be distributed to collaborating performers over the web, such as in Jordà's FMOL system (1999). Musical apps have taken advantage of mobile devices' always-on internet to include various kinds of collaboration. Smule's *Leaf Trombone* app introduced a "world stage" (Wang et al. 2015) where users from around the world were invited to critique performances with emoticons and short text comments. Mobile devices are also used in ensemble situations such as *MoPho* (Stanford Mobile Phone Orchestra) (Oh et al. 2010), *Viscotheque* (Swift 2013), *Pocket Gamelan* (Schiemer and Havryliv 2007), *ChoirMob* (d'Alessandro et al. 2012) and *Ensemble Metatone* (Martin et al. 2015); however, in these examples, the musicians played together in a standard, not geographically dispersed, concert situation.

Given that mobile devices are often carried by users at all times, it is natural to ask whether mobile ensemble experiences can be achieved outside of a typical concert. Collaborative configurations can be framed in a time-space matrix, that is, occurring together or apart in both location and time (Greenberg and Roseman 1998). While networked music performances (Carôt et al. 2007), with performers distributed in space, are well-documented (e.g., Bryan-Kinns 2004), collaborations across time are less thoroughly explored. Some locative performances (Behrendt 2012) have allowed asynchronous collaboration, for instance, in *AuRal* (Allison and Dell 2012), or *Tactical Sound Garden* (Shepard 2007). In these examples, users' interactions were stored at their location, allowing collaborations in a certain place, but separate in time.

To make music with users distributed in both space and time, some apps have allowed asynchronous layering of musical performances. *Glee Karaoke* (Hamilton et al. 2011) allows users to upload their vocal renditions of popular songs, and add layers to other performers' contributions. More conventional DAWs (digital audio workstations) offer social or collaboration features on mobile device (Meikle 2016) such as uploading whole tracks or short audio clips that other users can incorporate into their compositions. Our app, MicroJam, is distinguished from these other examples due to its focus on constrained and ephemeral music making as well as online collaboration.

Figure 2: MicroJam allows users to browse a timeline of performances (left), create new performances (centre), and reply, or play in duet, with previously recorded performances (right).

3 MicroJam

MicroJam is an app for creating, sharing, and collaborating with tiny touch-screen musical performance (Martin and Torresen 2017). It was designed to interrogate the possibilities for constrained social mobile performance. The app's design has been kept deliberately simple. The main screen (see Figure 2) recalls social-media apps for sharing images. Musical performances in MicroJam are limited to very short interactions, encouraging frequent and ephemeral creative contribution. MicroJam is an iOS app written in Swift and uses Apple's CloudKit service for backend cloud storage. The source code is freely available for use and modification by other researchers and performers (Martin 2018). In this section we will discuss the design of the app, the format of the tiny musical performances, and the synthesised instruments that are available.

3.1 Design

MicroJam allows users to do three primary activities (shown in Figure 2): browse and listen to other users' performances, create and share new performances using the touch screen; and record layers on top of previously shared performances. The interface for creative new performances is in the centre of Figure 2 and is called *jam!*. This screen features a square touch performance area which is initially blank. Tapping, swirling, or swiping anywhere in this area will create sounds and also start recording touch activity. All touch interaction in this area is visualised with a simple paint-style drawing that follows the user's touches. Touch interactions are simultaneously sent to a synthesised instrument to be sonified. After five seconds of touch interaction, the recording is automatically stopped (although the performer can continue to interact with the touch area). The recording can be subsequently replayed by tapping a "play" icon, or looped with the circular arrow icon. Users of MicroJam can choose the instrument used to sonify their interactions in the jam interface from a button in the top right. These synthesised instruments map a stream of touchscreen events—the location of a touch, and whether it is the start (touch down), or continuation (touch moved) of a previous gesture—to sound. The timbres and synthesis mappings are different for each instrument.

Previously recorded performances, and those recorded by other users and downloaded from the server, are listed in the *world* screen as shown on the left side of Figure 2. Each performance is represented by a visual trace of the touch-drawing captured during recording, along with an indication of the contributor's online handle. Any one of these performances can be played back in place in the world screen. When playing back, both the sound and visualised touch-interactions are replayed in the touch-area.

When viewing a previously saved performance in the world screen, the user can tap the reply icon (a curved arrow), to open a new layer on top of the recording. As shown in the right side of Figure 2, the previous as well as current touch-visualisations are shown and each layer is sonified separately. Multiple replies in MicroJam are possible which can result in several layers of performances being played back at once, allowing complex compositions.

3.2 Tiny touchscreen performances

MicroJam is intended to provide a musical experience where constraints are applied to the user's interaction to increase their creativity and lower the barriers of entry for musical performance. We argued above that constraints in social creativity systems could actually enhance users' creative power. In the context of a musical app, these constraints could lead to more frequent interactions and possibly higher creativity due to the lower stakes and effort. Musical interactions in MicroJam are similarly constrained to be *tiny* touchscreen performances as they are limited in the area and duration of interaction. We define a tiny performance as follows:

1. All touches take place in a square subset of the touchscreen.
2. Duration of the performance is *five* seconds.

Table 1: An excerpt from a tiny performance data record created in MicroJam.

time	x	y	z	moving
0.007805	0.276382	0.416080	38.640625	0
0.065901	0.286432	0.428141	38.640625	1
0.074539	0.286432	0.433166	38.640625	1
0.090817	0.290452	0.450251	38.640625	1
0.107149	0.298492	0.468342	38.640625	1
0.124072	0.309548	0.486432	38.640625	1

3. Only one simultaneous touch is recorded at a time.

Such performances require very little effort on the part of users. While some users may find it difficult to conceive and perform several minutes of music on a touchscreen device, five seconds is long enough to express a short idea, but short enough to leave users wanting to create another recording. It has been argued that five seconds is enough time to express a sonic object and other salient musical phenomena. (Godøy et al. 2010). While the limitation to a single touch may seem unnecessary on today's multi-touch devices, this stipulation limits tiny performances to monophony. In order to create more complex texture or harmony, performers must collaborate, or record multiple layers themselves.

For playback, storage, and transmission to other users, tiny touchscreen performances are recorded as simple comma-separated value files of recorded touch gestures. This data format records the user's performance movements in a compact manner (typical size is around 5KB), rather than the actual sound or abstract musical values such as notes and rests. The performance can later be recreated by sending these same touch event signals to MicroJam's synthesised instruments. The data format records each touch interaction's time (as an offset in seconds from the start of the performance), whether the touch was moving or not, x and y locations, as well as touch pressure (z), an example is shown in Table 1. The visual trace of performances is also stored as a PNG image for later use in the app, although this can also be reconstructed from the touch data.

Storing gestural control data, rather than audio, or high-level musical data such as MIDI, allows performances to benefit from updated synthesis routines in the app, and future enhancements to the visual interface. As noted in previous work on preserving touchscreen improvisation (Martin and Gardner 2016), this representation encodes information that might not be available in audio or MIDI recordings. In this research, we take advantage of this information to study tiny performances from a touch-gesture perspective.

3.3 Instruments in MicroJam

MicroJam includes nine different instruments (see Table 2) that map touches in the performance area to different synthesised sounds. This selection of instruments provides basic coverage of typical musical roles such as percussion (drums), bass (fmlead, wub), accompaniment (pad, keys), and lead (chirp, strings). While far from an exhaustive collection, these instruments allow exploration of different musical ideas, both through their different timbres as well as the different touch to sound mappings used in each one. Descriptions and mapping details for each instrument is given in Table 2.

The instruments are implemented in Pure Data and make use of the `rjlib` library (Barknecht 2011) for some synthesis routine implementations. They are loaded in the app via `libpd` (Brinkmann et al. 2011). The instruments are controlled by continuous inputs of x, y values from the single touch point in performance area (z, pressure, is so far not used as it is not available in all devices). Each instrument is responsible for its specific mappings of these values to higher level musical properties such as pitch, timbre and control of audio effects. For example, the fmlead sound, a simple FM synthesiser, maps initial x-values from a tap or swipe to a bass register pitch on a continuous range (MIDI notes 36–60) without quantisation to a scale or chromatic tones. The y-value is mapped to volume. Tapping the screen triggers a very short note, while swiping creates a sustained sound until the touch is released. For continuous swipes, the distance of the present touch-point to the initial one (dx and dy) is calculated; dx is used to control pitch bend, and dy is mapped to reverb and delay effects as well as mixing in a copy of the sound in a lower octave. A similar mapping scheme is used for the other pitched sounds, see Table 2 for further details. For the "drum" sound, different synthesised drumset sounds (bass drum, snare drum, hihat, and crash cymbal) are triggered from each quadrant of the screen and the swipes trigger a roll. In general, the instruments in MicroJam are designed to support fun audio sketches rather than song production. Constraints such as the lack of quantisation on our pitched instruments are intended to limit precise note-playing and emphasise ephemeral improvisations.

4 Studying Tiny Performances

In this section we describe an investigation of how users interact with MicroJam through the lens of the tiny performances that have been collected in the app. Since early prototypes of MicroJam were developed, the app has been distributed and demonstrated among researchers, students, and the music tech-

Table 2: Descriptions and mapping details of each instrument in MicroJam.

instrument	description	X	Y	dX	dY
chirp	Basic sine oscillator sound.	pitch	mix lower octave	pitch bend	
drums	Drum sounds (bass drum, snare drum, hi-hat, crash cymbal) triggered from each quadrant. Swipes trigger rolls.	inst.	inst.	pitch bend	reverb/delay fx (wet/dry)
fmlead	Simple two operator FM synthesiser that plays in a bass register.	pitch	volume	pitch bend	mix lower octave, reverb/delay fx (wet/dry)
keys	Phase modulation Rhodes-like keyboard sound.	pitch	volume	pitch bend	modulation depth
pad	Sawtooth wave pad synth.	pitch	volume	pitch bend	tremolo depth, reverb/delay fx (wet/dry)
quack	Wave packet synth with analogue-like sound.	pitch	timbre	pitch bend	
strings	Karplus-Strong plucked guitar synthesiser.	pitch	volume	pitch bend	reverb/delay fx (wet/dry)
leadguitar	Karplus-Strong synthesiser with distortion.	pitch	volume	pitch bend	reverb/delay fx (wet/dry)
wub	Tremolo “wub wub” bass sound.	pitch, timbre	tremolo rate, timbre	pitch bend	

nology community, and these testers and early users uploaded performances to the app's cloud database. To date, more than 1600 tiny performances are available in this database, allowing us to gain insight into the musical potential of MicroJam and the concept of tiny touchscreen performances.

Our analysis of the tiny performances is made at three levels of abstraction: individual touch events, gestures or groups of touch events, and whole performances. At the touch event level, we consider individual touch events that may be part of a swipe across the screen, or single taps. At the gesture level, we consider groups of these touch events that constitute a single "note" or interaction: either individual taps, or the collection of events that form a swipe. At the performance level, we consider descriptors of each complete 5-second performance and how these vary by the instrument that was used, we also analyse the visual trace of the resulting performance. These levels reveal different aspects of the users' performance behaviour; while the whole performance level demonstrates their broad artistic intentions, the gestural and touch levels expose small-scale interactions.

4.1 Participants and Data Sources

Tiny performances for this investigation came from two databases: a development database which is only accessible from instances of MicroJam installed on the authors' test devices, and a public database accessible from beta and published versions of MicroJam. Performances in the development database were made at testing and demonstration sessions taking place in our lab, at conferences, and at other events. Most of the participants in these sessions were university students and researchers in music technology or computer science. These participants had a range of music experience from untrained to professional. The public database was accessed from beta versions of the app as well as the published app store version. Beta versions were distributed to interested members of the computer music and technology community who requested invitations through social media and at conferences. Since the public release of the app, performances in this database have been contributed by unknown members of the public.

Unlike most music apps, all performances saved in MicroJam's public database are openly accessible through the app and through Apple's CloudKit API. Personal data (e.g., real names, email addresses, IP addresses) are not included in this data. While the use of public social media data (e.g., studies of text scraped from Twitter) for research is commonplace, there remain ethical concerns about whether users are comfortable with such use (Fiesler and Proferes 2018). In our case, MicroJam's privacy policy highlights our research intentions, and the number of users from the published version of

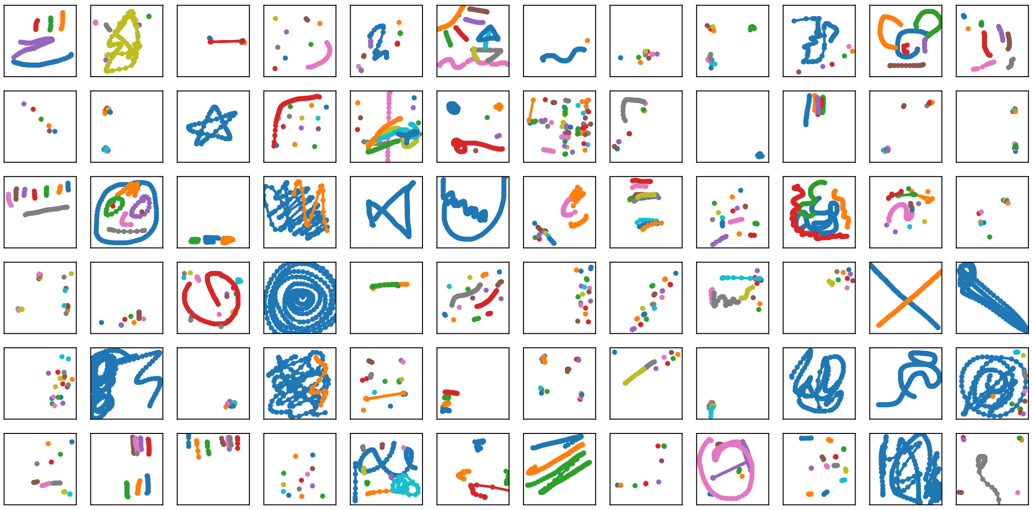


Figure 3: The visual trace of a selection of MicroJam performances with each swipe coloured differently. Some different performance styles are visible, for example: taps (dots), single long swipes (long lines or curves), repeated strokes (such as parallel lines), and drawing an image (such as a face). Some of the interactions appear to be predominantly visual, while others are exploratory scribbles with little visual coherence.

MicroJam is, so far, small compared to those who installed the app through private beta testing.

Within our dataset, 98 unique CloudKit accounts are represented including two accounts created for our demonstration devices. While many users (including the developers) performed on our demonstration devices, we assume the other accounts are associated with individual users. The dataset contains a total of 1633 performances. 761 of these performances are from our demonstration accounts while the remaining 872 performances are from unknown users. The median number of performances per user was 3, while 25% of users created more than 6 performances with the app.

Performances from the first author's non-demonstration account were excluded from this dataset. Performances on the demonstration devices, including some by the first author, were retained as these included performances from many users and further identification of individual performers was not possible.

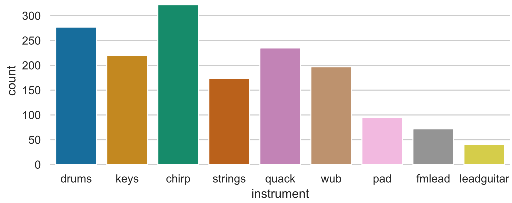


Figure 4: Number of performances with each instrument in our dataset. The default instrument, "chirp" is most popular, followed by drums.

4.2 Performance Level Investigation

The visualisations of a subset of tiny performances are reproduced in Figure 3. This figure shows the variety of touch-interaction styles that have been generated by performers. Many of the interactions are abstract, resembling scribbles that show the user experimenting with the synthesis mapping of the jamming interface. Some performances contain patterns where performers have repeated rhythmic motions in different parts of the touch area. A number of the performances are recognisable images: figures, faces, and words. We can characterise the visual appearance of performances under the following broad styles: taps, swipes, long swipe, mixture, image, and text. Tap and swipe performances focus on these fundamental touch gestures, while long swipe performances seem to consist of only one swipe, and mixture performance include multiple of these styles. Image and text performances appear to focus on the visual meaning of the finished trace, likely with less emphasis given to the resulting sound.

Of the 1633 performances in the dataset, 424, or 26%, are replies. As replies of replies are possible in MicroJam, it is interesting to see how long potential chains of replies are in terms of number of performance layers (see Table 3). Of the 424, 299 have just two layers. While there are 83 performances with 3 layers, there are very few with 7 and 8 layers (2 each). This data suggests that while users have made some use of the reply function, they have only rarely explored its potential for creating complex layered performances. Further development work could help encourage users to create longer performances; for instance, highlighting complex performances in the browsing screen.

While performances with all instruments are represented in the dataset, the most popular instrument is chirp (the default choice) with 322 performances. Figure 4 shows that the next five most popular instruments (drums, keys, quack, strings, wub) all have around 200 performances, but that fmlead, pad, and leadguitar have less than 100 each. These instruments were added

Table 3: Counts of occurrences for different reply chain lengths.

chain length	2	3	4	5	6	7	8
count	299	83	24	9	5	2	2

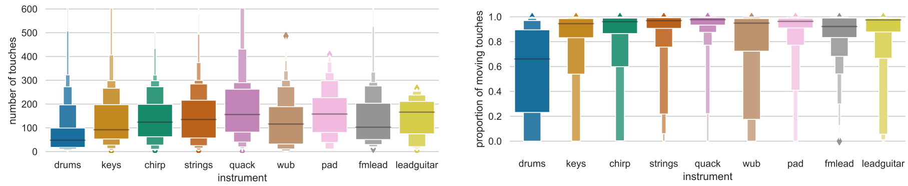
to the app in later revisions, and may have been less obvious in the list of instruments.

4.3 Analysis by Touch Event

The dataset includes 238,743 touch events. As set out in the tiny performance definition above, a touch event can either be a *touch-down* (when the user's finger hits the touchscreen), or a *touch-moved* (when the user's finger has moved without leaving the touchscreen). These are distinguished by a binary value, "moving", in the dataset. These events are triggered by iOS touchscreen callbacks `touchesBegan` and `touchesMoved` respectively. Only 13,077 touch events in the dataset are non-moving compared to 225,666 moving touches, this is because whenever a user swipes during a performance a large number of moving touches are generated, while only one touch-down occurs.

Figure 5a shows the distribution of the number of touch events recorded per performance grouped by instrument used. This shows that for all instruments except drums performances had a median of between 90 and 170 touch events. The median number of touch events for drums was 48, much lower than the other instruments. This is explained by Figure 5b which shows the proportion of touch events that were moving in each performance. For drums, many more touch events were taps, rather than swipes, which resulted in fewer touch events for a given performance.

Two interesting statistics are the time differences between consecutive touch events (*dt*), and the onscreen distance between them measured as a proportion of the performance area. Distributions of these statistics are shown in Figure 6. As expected, values of *dt* and distance for moving touches tend to be small (touch events in iOS are generally produced at the screen's refresh rate—60Hz for most devices at present), although there are slower outliers which could have been caused by errors in the user-interface code or drops in performance. The median *dt* between moving touches is only 0.017s ($\approx$ 60Hz) compared with 0.219s for non-moving touches. The interquartile range of *dt* for non-moving touches is 0.094s—0.386s, this gives an indication that performers tend not to leave much time in between interactions and the resulting tiny performances would not have much temporal "space". Similarly, we can observe that non-moving touches tend to have moved within a relatively small proportion of the performance area (median = 0.193, interquartile range



(a) Distribution of the total count of touchpoints in each performance for each instrument.

(b) Distribution of moving vs. non-moving touchpoints for each instrument.

Figure 5: Distributions of touchpoint properties grouped by instrument shown as letter-value plots (Hofmann et al. 2017). Each instrument had a similar number of touchpoints per performance with somewhat fewer for drums. All instruments except drums are dominated by moving touches.

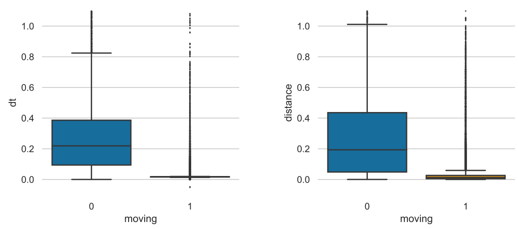


Figure 6: Distributions of touch event dt values (left) and screen distance (right) separated by whether the touch was moving or not.

$= [0.048, 0.436]$). This can be observed in some of the example performances in Figure 3 where a user has tapped repeatedly in the same part of the performance area.

Figure 7 shows the distribution of touch events across the touchscreen performance area (obtained with a bivariate kernel density estimate). This allows us to investigate where users have most commonly interacted with the performance area to play sounds. We can observe that touches cover the whole performance area; however, more touches occur on the diagonals and in the upper right quadrant. Relatively few touches extend all the way to the edges.

These analyses suggest that users tend not to explore the potential of space in their performances, both in terms of time and the touchscreen area. Given the time limitation of five seconds, it is understandable that users would prefer to squeeze in as much activity as possible. However, a small number of interactions could also be effective by allowing pauses that add structure to the performance (Sutton 2002). Taken together, these results could inform future synthesis mappings in the app. For instance, a mapping

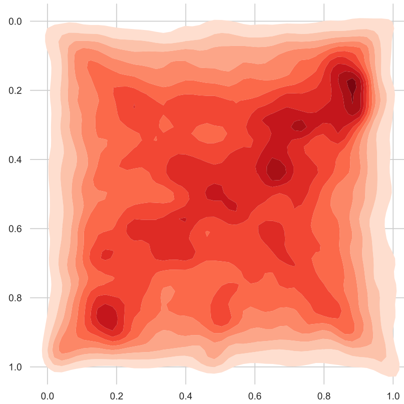


Figure 7: The distribution of touch event locations across the touchscreen performance area (bivariate kernel density estimation) where darker colours indicate higher touch event density. Touches broadly cover the whole performance area, but are more prominent on the diagonals and particularly in the upper right corner.

could produce unexpected or interesting sounds if the next touch event is far away in space or time. Given that users tend not to use the edge of the performance area, these areas could be mapped to more extreme sounds (e.g., with distortion or delay effects). Similar mappings have been explored in instruments such as "Crackle" (Reus 2011).

4.4 Analysis by Gesture

In this section we analyse performances from the perspective of tap and swipe gestures, the two fundamental touchscreen interactions available in MicroJam's interface. A swipe is a sequence of multiple touch events that can be defined as a touch-down followed by a non-zero number of touch-moved events. The dataset contains 7237 such swipes, compared with 5840 true taps where a touch down was not followed by a touch moved event. These swipes represent one of the more important phenomena in tiny-performances as they represent the actions formed by the majority of touch-points. We extracted swipes from each performance in the dataset by dividing them by touch down events and discarding all divisions with only a touch-down. Before analysing swipes we removed erroneous touch events with $dt < 0.008$ (corresponding to the maximum 120Hz touch scan rate in iOS), these touch events could have been caused by multiple touches being interpreted as one movement. This procedure excluded 215 swipes which were left with 1 or 0 touch events. 71 swipes that were longer than 5 seconds were excluded. We were then able to

Table 4: Descriptive statistics of swipes in the dataset.

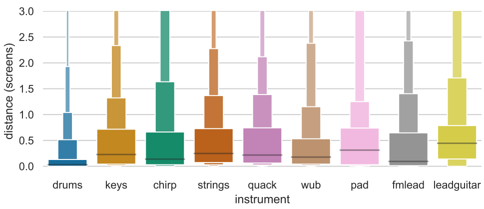
statistic	length (events)	time (s)	mean velocity	distance	max velocity
mean	28.064	0.518	1.432	0.643	4.041
std	52.645	0.965	2.706	1.807	8.762
min	2	0.008	0.000	0.000	0.000
25%	4	0.057	0.281	0.023	0.673
50%	7	0.121	0.767	0.135	1.773
75%	26	0.506	1.574	0.590	3.743
max	478	4.999	53.870	49.610	107.740

perform analyses that characterise swiping behaviour seen in our dataset.

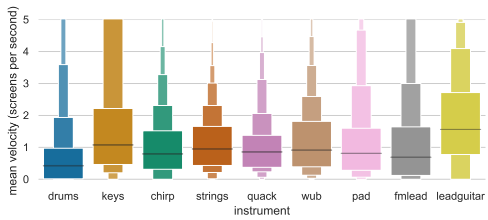
Table 4 shows descriptive statistics on the 7022 valid swipes. The majority were short in time and on-screen distance (measured in proportions of the performance width covered). 75% of swipes were shorter than 0.506s in duration and the median swipe time was only 0.121s. The median distance was 0.135 area widths and 75% of swipes traced less than 0.59 of the area width. These results seem inconsistent with the appearance of the visual traces shown in Figure 3 where the images appear to be dominated by long continuous swipes. The dataset does contain long swipes, up to the whole 5s in time and almost 50 area widths. These long swipes are visually dominant, especially given that they can cover up some smaller interactions, but they are outnumbered by the shorter swipes that make up the vast majority of gestures. A small number of swipes seem to have incredibly fast movements. These are due to instances where multiple touches on the screen have been erroneously interpreted as movement.

In Figure 8, we show the distributions of time, distance, and mean velocity for each instrument in MicroJam. One-way ANOVA tests on each measurement confirm that there are significant effect due to instrument ($p < 0.001$). In particular, drum performances have much shorter swipes than any of the other instruments in terms of both distance traced and time. This could be due to many attempted "taps" that were actually short swipes with just a few touch-points. The keys instrument seemed to gather some of the fastest swipes.

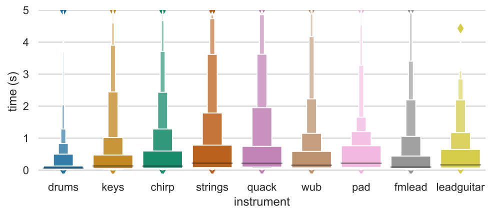
To gain an intuitive idea of how these swipes looked, we have visualised selections of swipes of different time-length, these are shown in Figure 9. First, the quartiles for the time dimension were calculated (see Table 4), then 200 swipes were sampled from each quartile randomly. The quickest 25% of swipes are almost always straight lines with some spanning quite far across the screen. The two quartiles around the median length show much



(a) Distance travelled over each swipe.



(b) Mean velocity over each swipe.



(c) Time taken for each swipe.

Figure 8: The distribution of swipe statistics for different instruments shown as letter-value plots (Hofmann et al. 2017).

variation in expression. Swipes shorter than the median rarely have more than a subtle curve, while those above the median show curves that could have an expressive effect on the pitch and timbre of the resulting sounds. In the upper quartile of length, swipes can cover the whole performance area or trace complex patterns. These swipes could represent longer notes, parts of drawings, or whole 5-second performances.

The 2D traces of performances in figures 3 and 9 do not show the velocity of swipes—a quantity with much expressive potential. In Figure 10, we visualise the normalised velocity curves for selections of swipes of different lengths. The shortest swipes have only 2 or 3 touch points and the velocity tends to only increase, indicate a quick flicking movement. The next quartile shows a more expressive curve, with a quick rise and slower release as the touch point stops moving before the end of the swipe. The third quartile shows the possibility for multiple peaks and valleys in the velocity, perhaps indicating changes in direction of the moving touch point. Again, only the fourth quartile shows extensive expressive behaviour such as repeating peaks in velocity that could indicate a rhythmic movement pattern over a longer swipe.

The analysis of swipes in MicroJam has left us some important insights. Most importantly, the majority of swipes are short—three quarters are less than 0.506 seconds—however, the longest swipes have more scope for expres-

Figure 9: Random selections of 200 swipes from each quartile of swipe-length (in time) represented in the dataset.

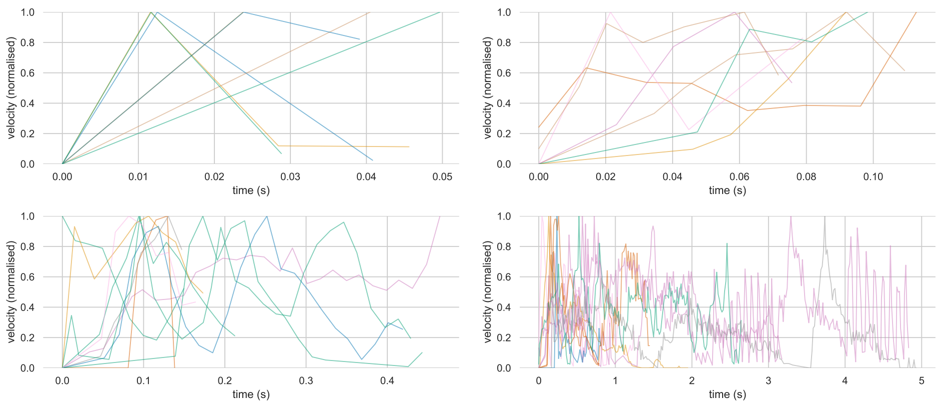


Figure 10: The normalised velocity curves of random selections of 20 swipes from each time quartile represented in the dataset. The shortest swipes tend to be strictly increasing in velocity while the longer two quartiles show some temporal activity such as pulsing velocity that could indicate tracing back and forth across the screen.

sive behaviour. This has implications for future instrument design that should allow more detailed expression with very short interactions, e.g., by slowing down the effect a swipe has on audio effects or timbral changes to make them more noticeable. Alternatively, long swipes could be encouraged. It could be if the visual impact of long swipes was reduced by fading them out over time, users might feel more confident to explore them more frequently. Further refinements to instruments such as "drums" that reward longer swipes with interesting sounds (e.g., pitch bends on toms or cymbals) could also encourage such behaviour.

4.5 Discussion

The results above allow us to characterise how users perform within the constraints of MicroJam's tiny performance idiom. We know that they perform in different broad styles including abstract gestures as well as images and text. While visually meaningful performances draw the eye, the dataset is dominated by very short swipes and taps which are typical of the more abstract performance styles. It is questionable whether image and text explorations lead to rewarding musical experiments, and it may be more appropriate to focus on improving the expressive potential of other performance styles. As for the social aspects of MicroJam, while the reply function has certainly been used in the dataset, few multi-layered performances are present which limits the conclusions we can draw. Future revisions of MicroJam could emphasise replying and collaboration rather than just performance creation.

Four of our findings from analysis of MicroJam's touch data can be extrapolated into design recommendations for future versions of MicroJam and other touchscreen music systems:

1. At present, few performances have more than two layers. To encourage more complex performances, multi-layered performances could be celebrated within the app. Multi-layered performances could be highlighted in the world feed, and opportunities to reply presented more actively.

2. The edges of the performance area are rarely used by performers. The instrument mappings could be altered to use these spaces to create more exotic or experimental sounds that reward the user's exploration.

3. Very short swipes are the most common gesture. To emphasise the impact of these interactions, they could be emphasised more in the sound design for MicroJam.

4. Long swipes are rare, yet they dominate the visual trace of performances. The visual impact of long swipes could be reduced, for instance, by

fading out the long tails of interactions. This might allow multiple of them to be used without overwhelming the touch area.

So far, MicroJam has mainly been used in test and demo environments, and few users have shared large numbers of performances. As a result, the performances analysed in this dataset are generally by inexperienced users. We would expect, however, that as for other instruments, MicroJam users would improve with practice, and develop new styles. Future work could seek to identify changes in tiny performance style over time.

One aspect of analysis that has not been mentioned is modelling and generation of tiny performances with machine learning. Previous research has already discussed a mixture density recurrent neural network model for generating and responding to tiny performances (Martin and Torresen 2018). This system is available in the app to provide an automatic reply to a performance on demand and generates the same control data format as the tiny performances. In future work we could explore the potential for developing tailored models of individual users' styles which could even provide control over the kind of gestures (for instance, short swipes or taps) that are provided in an automatic response. These models could also be used to demonstrate effective use of the gestures highlighted in the above recommendations as part of a performance training feature. Future studies could also compare longer performances with MicroJam to the present 5-second format to confirm whether the constrained performance length affects performers' interactions.

5 Conclusions

In this paper we have presented the design for MicroJam, a social mobile music app for creating touchscreen performances and defined the tiny performance format. We have investigated this app through a data-driven analysis of more than 1600 performances created by more than 97 individual users. This investigation has revealed how users perform in the tiny touchscreen idiom and revealed contradictions and complexities in these performances. We now know that short swipes are the most common gesture, yet long swipes dominate the visual appearance of performances. We found that the edges of the performance area are not well-explored by performers and that users do not explore space and time as much as they should. Yet, the visual representations in performances are varied and expressive. These findings enhance our understanding of how users interact with free-form touchscreen music systems and could apply to a variety of app designs.

MicroJam is an example of a social app centred on musical creation rather than written and visual media. We have argued that such apps could take advantage of the ubiquity of mobile devices by allowing users to collaborate asynchronously and in different locations, and shown that these modes of interaction are relatively unexplored compared to more conventional ensemble performances. The focus on time-limited tiny performances represents a new approach to asynchronous musical collaboration. Taking inspiration from the constrained contributions that typify social media apps, MicroJam limits users to five-second touchscreen performances, but affords them extensive opportunities to browse, playback, and collaborate through responses. MicroJam's tiny performance format includes a complete listing of the touch interactions and so allows performances to be easily distributed, visualised, and studied.

Our novel data-driven investigation examined 1633 performances consisting of 238,743 touch events. Our quantitative method sets this work apart from previous research that has focussed on users' qualitative experience. The performances were analysed at the levels of individual touch events, grouped touch gestures, and whole performances. The investigation revealed the variety of styles used in performances but that fewer performances than desired were replies. Examining touch points showed that the edges of the performance area was not used as much as the centre and main diagonals, and that moving touches, rather than taps, dominated the dataset. Grouping touches into swipes showed that while long swipes are more visually apparent, the vast majority of swipe gestures are actually short. This data-driven method is a contribution of this work, and could be applied to other studies of musical performance systems on touchscreens and other interfaces.

The analysis in this article has suggested that even a simple and constrained touchscreen interface can lead to a variety of styles and unexpected musical interactions. While constraining the length of performances may have increased the number recorded, and made it easier to collaborate using musical replies, it could have curbed users' gestural exploration with the touch screen. We have discussed how our findings might inform design revisions that could better align MicroJam's capacity for musical expression with user behaviour. These revisions may encourage more expressive performances in MicroJam users, and more collaboration, without increasing the effort required to generate tiny touchscreen performances. For music making, as opposed to appreciation, to be widely adopted as part of everyday social media interactions, this balance between constraint and expression will need to be further examined and addressed. We posit that a data-driven approach to mobile music performance, examining musical data generated by users, can be used to further examine this balance in MicroJam and other systems for mobile musical creativity.

Funding

This work was partially supported by The Research Council of Norway through the Engineering Predictability with Embodied Cognition (EPEC) project, under grant agreement 240862, and the Centres of Excellence scheme, project number 262762.

Acknowledgements

We wish to thank participants in our study as well as beta testers and others who tried MicroJam. We also thank Henrik Brustad and Benedikte Wallace who worked on MicroJam as research assistants.

References

Jesse Allison and Christian Dell. 2012. AuRal: A Mobile Interactive System for Geo-Locative Audio Synthesis. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. University of Michigan, Ann Arbor, Michigan, 3 pages. `http://www.nime.org/proceedings/2012/nime2012_301.pdf`

Frank Barknecht. 2011. rj - Abstractions for getting things done. In *Proceedings of the Pure Data Convention*. Faculty of Media, Bauhaus-Universität Weimar, Bauhaus-Universität Weimar, Weimar, Germany, 9 pages.

Timothy J. Barraclough, Dale A. Carnegie, and Ajay Kapur. 2015. Musical Instrument Design Process for Mobile Technology. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, Edgar Berdahl and Jesse Allison (Eds.). Louisiana State University, Baton Rouge, Louisiana, USA, 289–292. `http://www.nime.org/proceedings/2015/nime2015_313.pdf`

Frauke Behrendt. 2012. The sound of locative media. *Convergence* 18, 3 (2012), 283–295. `https://doi.org/10.1177/1354856512441150`

Peter Brinkmann, Peter Kirn, Richard Lawler, Chris McCormick, Martin Roth, and Hans-Christoph Steiner. 2011. Embedding Pure Data with libpd. In *Proceedings of the Pure Data Convention*. Bauhaus-Universität Weimar, Weimar, Germany, 8 pages.

http://www.uni-weimar.de/medien/wiki/PDCON:Conference/Embedding_Pure_Data_with_libpd:_Design_and_Workflow

Nick Bryan-Kinns. 2004. Daisyphone: The Design and Impact of a Novel Environment for Remote Group Music Improvisation. In *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques* (Cambridge, MA, USA) *(DIS '04)*. ACM, New York, NY, USA, 135–144. https://doi.org/10.1145/1013115.1013135

Alexander Carôt, Pedro Rebelo, and Alain Renaud. 2007. Networked Music Performance: State of the Art. In *Audio Engineering Society 30th International Conference*. AES, New York, NY, 1–7. http://www.aes.org/e-lib/browse.cfm?elib=13914

A. G. D. Correa, I. K. Ficheman, M. d. Nascimento, and R. d. D. Lopes. 2009. Computer Assisted Music Therapy: A Case Study of an Augmented Reality Musical System for Children with Cerebral Palsy Rehabilitation. In *Ninth IEEE International Conference on Advanced Learning Technologies*. IEEE, New York, NY, 218–220. https://doi.org/10.1109/ICALT.2009.111

Nicolas d'Alessandro, Aura Pon, Johnty Wang, David Eagle, Ehud Sharlin, and Sidney Fels. 2012. A Digital Mobile Choir: Joining Two Interfaces towards Composing and Performing Collaborative Mobile Music. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. University of Michigan, Ann Arbor, Michigan, 4 pages. http://www.nime.org/proceedings/2012/nime2012_310.pdf

Sanjeev Dewan and Jui Ramaprasad. 2014. Social media, traditional media, and music sales. *MIS Quarterly* 38, 1 (2014), 101–121.

Georg Essl and Sang Won Lee. 2018. Mobile Devices as Musical Instruments - State of the Art and Future Prospects. In *Music Technology with Swing. CMMR 2017 (Lecture Notes in Computer Science, Vol. 11265)*, M. Aramaki, M. Davies, R. Kronland-Martinet, and Ystad S. (Eds.). Springer, Cham, 525–539.

G. Essl and M. Rohs. 2009. Interactivity for mobile music-making. *Organised Sound* 14, 2 (2009), 197–207. https://doi.org/10.1017/S1355771809000302

Stu Favilla and Sonja Pedell. 2013. Touch Screen Ensemble Music: Collaborative Interaction for Older People with Dementia. In *Proceedings of the 25th Australian Computer-Human Interaction Conference (OzCHI*

'13). ACM, New York, NY, USA, 481–484. https://doi.org/10.1145/2541016.2541088

Casey Fiesler and Nicholas Proferes. 2018. "Participant" Perceptions of Twitter Research Ethics. *Social Media + Society* 4, 1 (2018), 1–14. https://doi.org/10.1177/2056305118763366

Lalya Gaye, Lars Erik Holmquist, Frauke Behrendt, and Atau Tanaka. 2006. Mobile Music Technology: Report on an Emerging Community. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '06)*. IRCAM Centre Pompidou, Paris, France, 22–25. http://www.nime.org/proceedings/2006/nime2006_022.pdf

Kristina Gligorić, Ashton Anderson, and Robert West. 2018. How Constraints Affect Content: The Case of Twitter's Switch from 140 to 280 Characters. In *Proceedings of the International AAAI Conference on Web and Social Media (ICWSM)*. AAAI Press, Palo Alto, CA, 596–599. https://aaai.org/ocs/index.php/ICWSM/ICWSM18/paper/view/17895

Rolf Inge Godøy, Alexander Refsum Jensenius, and Kristian Nymoen. 2010. Chunking in Music by Coarticulation. *Acta Acustica united with Acustica* 96, 4 (2010), 690–700. https://doi.org/10.3813/AAA.918323

Saul Greenberg and Mark Roseman. 1998. *Using a Room Metaphor to Ease Transitions in Groupware*. Technical Report 98/611/02. Department of Computer Science, University of Calgary.

Michael Gurevich, Adnan Marquez-Borbon, and Paul Stapleton. 2012. Playing with Constraints: Stylistic Variation with a Simple Electronic Instrument. *Computer Music Journal* 36, 1 (2012), 23–41. https://doi.org/10.1162/COMJ_a_00103

Robert Hamilton, Jeffrey Smith, and Ge Wang. 2011. Social Composition: Musical Data Systems for Expressive Mobile Music. *Leonardo Music Journal* 21 (December 2011), 57–64. https://doi.org/10.1162/LMJ_a_00062

Heike Hofmann, Hadley Wickham, and Karen Kafadar. 2017. Letter-Value Plots: Boxplots for Large Data. *Journal of Computational and Graphical Statistics* 26, 3 (2017), 469–477. https://doi.org/10.1080/10618600.2017.1305277

David John. 2013. Updating the Classifications of Mobile Music Projects. In *Proceedings of the International Conference on New Interfaces for Musical*

Expression. Graduate School of Culture Technology, KAIST, Daejeon, Republic of Korea, 301–306.

Sergi Jordà. 1999. Faust Music On Line (FMOL) An approach to Real-time Collective Composition on the Internet. *Leonardo Music Journal* 9 (1999), 5–12. https://doi.org/10.1162/096112199750316730

Tejaswinee Kelkar and Alexander Refsum Jensenius. 2018. Analyzing Free-Hand Sound-Tracings of Melodic Phrases. *Applied Sciences* 8, 1 (2018), 21 pages. https://doi.org/10.3390/app8010135

David Kim-Boyle. 2009. Network Musics: Play, Engagement and the Democratization of Performance. *Contemporary Music Review* 28, 4-5 (2009), 363–375. https://doi.org/10.1080/07494460903422198

Charles Martin and Henry Gardner. 2016. A Percussion-Focussed Approach to Preserving Touch-Screen Improvisation. In *Curating the Digital: Spaces for Art and Interaction*, David England, Thecla Schiphorst, and Nick Bryan-Kinns (Eds.). Springer International Publishing, Switzerland, 51–72. https://doi.org/10.1007/978-3-319-28722-5_5

Charles Martin, Henry Gardner, and Ben Swift. 2015. Tracking Ensemble Performance on Touch-Screens with Gesture Classification and Transition Matrices. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '15)*, Edgar Berdahl and Jesse Allison (Eds.). Louisiana State University, Baton Rouge, LA, USA, 359–364. http://www.nime.org/proceedings/2015/nime2015_242.pdf

Charles Martin, Henry Gardner, Ben Swift, and Michael Martin. 2016. Intelligent Agents and Networked Buttons Improve Free-Improvised Ensemble Music-Making on Touch-Screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2295–2306. https://doi.org/10.1145/2858036.2858269

Charles P. Martin. 2018. MicroJam Source Code. Git Repository. https://doi.org/10.5281/zenodo.1412274

Charles P. Martin and Jim Torresen. 2017. Exploring Social Mobile Music with Tiny Touch-Screen Performances. In *Proceedings of the 14th Sound and Music Computing Conference (SMC '17)*, Tapio Lokki, Jukka Pätynen, and Vesa Välimäki (Eds.). Aalto University, Espoo, Finland, 175–180.

Charles P. Martin and Jim Torresen. 2018. RoboJam: A Musical Mixture Density Network for Collaborative Touchscreen Interaction. In

Computational Intelligence in Music, Sound, Art and Design: International Conference, EvoMUSART (Lecture Notes in Computer Science, Vol. 10783), Antonios Liapis, Juan Jesús Romero Cardalda, and Anikó Ekárt (Eds.). Springer International Publishing, Switzerland, 161–176. https://doi.org/10.1007/978-3-319-77583-8_11

George Meikle. 2016. Examining the Effects of Experimental/Academic Electroacoustic and Popular Electronic Musics on the Evolution and Development of Human-Computer Interaction in Music. *Contemporary Music Review* 35, 2 (2016), 224–241. https://doi.org/10.1080/07494467.2016.1221634

Max Neuhaus. 1977. Radio Net. [Live Performance Archived at UbuWeb]. http://www.ubu.com/sound/neuhaus_radio.html

Jieun Oh, Jorge Herrera, Nicholas J. Bryan, Luke Dahl, and Ge Wang. 2010. Evolving the Mobile Phone Orchestra. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '10)*, Kirsty Beilharz, Andrew Johnston, Sam Ferguson, and Amy Yi-Chun Chen (Eds.). University of Technology Sydney, Sydney, Australia, 82–87. http://www.nime.org/proceedings/2010/nime2010_082.pdf

Miriam Redi, Neil O'Hare, Rossano Schifanella, Michele Trevisiol, and Alejandro Jaimes. 2014. 6 Seconds of Sound and Vision: Creativity in Micro-Videos. In *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. IEEE, New York, NY, 4272–4279. https://doi.org/10.1109/CVPR.2014.544

Jonathan Reus. 2011. Crackle: A mobile multitouch topology for exploratory sound interaction. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '11)*, Alexander Refsum Jensenius, Anders Tveit, Rolf Inge Godøy, and Dan Overholt (Eds.). University of Oslo, Oslo, Norway, 377–380. http://www.nime.org/proceedings/2011/nime2011_377.pdf

Stephanie Scheffel and Bill Matney. 2014. Percussion Use and Training: A Survey of Music Therapy Clinicians. *Journal of Music Therapy* 51, 1 (2014), 39. https://doi.org/10.1093/jmt/thu006

Greg Schiemer and Mark Havryliv. 2007. Pocket Gamelan: Swinging phones and ad-hoc standards. In *Proceedings of the 4th International Mobile Music Workshop*. STEIM, Amsterdam, 2 pages.

Kevin Schlei. 2012. TC-11: A Programmable Multi-Touch Synthesizer for the iPad. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '12)*, G. Essl, B. Gillespie, M. Gurevich, and S. O'Modhrain (Eds.). University of Michigan, Ann Arbor, Michigan, 4 pages. `http://www.nime.org/proceedings/2012/nime2012_230.pdf`

Mark Shepard. 2007. Tactical Sound Garden Toolkit. In *ACM SIGGRAPH 2007 Art Gallery* (San Diego, California) *(SIGGRAPH '07)*. ACM, New York, NY, USA, 219–. `https://doi.org/10.1145/1280120.1280176`

Jeffrey C. Smith. 2013. *Correlation analyses of encoded music performance.* Ph.D. Dissertation. Stanford University. `https://ccrma.stanford.edu/damp/publications/jeffsmiththesis.pdf`

Patricia D Stokes. 2008. Creativity from Constraints: What can we learn from Motherwell? from Modrian? from Klee? *The Journal of Creative Behavior* 42, 4 (2008), 223–236. `https://doi.org/10.1002/j.2162-6057.2008.tb01297.x`

Julie P. Sutton. 2002. "The Pause That Follows".. *Nordic Journal of Music Therapy* 11, 1 (2002), 27–38. `https://doi.org/10.1080/08098130209478040`

Ben Swift. 2013. Chasing a Feeling: Experience in Computer Supported Jamming. In *Music and Human-Computer Interaction*, Simon Holland, Katie Wilkie, Paul Mulholland, and Allan Seago (Eds.). Springer, London, UK, 85–99. `https://doi.org/10.1007/978-1-4471-2990-5_5`

Atau Tanaka. 2010. Mapping Out Instruments, Affordances, and Mobiles. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '10)*, Kirsty Beilharz, Andrew Johnston, Sam Ferguson, and Amy Yi-Chun Chen (Eds.). University of Technology Sydney, Sydney, Australia, 88–93. `http://www.nime.org/proceedings/2010/nime2010_088.pdf`

Sebastian Trump and Jamie Bullock. 2014. Orphion: A Gestural Multi-Touch Instrument for the iPad. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '14)*, Baptiste Caramiaux, Koray Tahiroglu, Rebecca Fiebrink, and Atau Tanaka (Eds.). Goldsmiths, University of London, London, UK, 159–162. `http://www.nime.org/proceedings/2014/nime2014_277.pdf`

Ge Wang. 2014. Ocarina: Designing the iPhone's Magic Flute. *Computer Music Journal* 38, 2 (2014), 8–21. https://doi.org/10.1162/COMJ_a_00236

Ge Wang, Jieun Oh, and Tom Lieber. 2011. Designing for the iPad: Magic Fiddle. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '11)*, Alexander Refsum Jensenius, Anders Tveit, Rolf Inge Godøy, and Dan Overholt (Eds.). University of Oslo, Oslo, Norway, 197–202. http://www.nime.org/proceedings/2011/nime2011_197.pdf

Ge Wang, Spencer Salazar, Jieun Oh, and Robert Hamilton. 2015. World Stage: Crowdsourcing Paradigm for Expressive Social Mobile Music. *Journal of New Music Research* 44, 2 (2015), 112–128. https://doi.org/10.1080/09298215.2014.991739