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ORIGINAL ARTICLE

Design and evaluation of a digitally active drum

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Abstract
Despite the ever growing variety and popularity of commercially available electronic percussion (EP) instruments, there are still a significant number of active musicians who prefer to use acoustic drums. Digitally active drum (DAD) is an enhanced snare drum that provides sonic capabilities associated with digital musical instruments in the form of a traditional acoustic drum allowing full use of acoustic drumming gesture vocabulary. By using an in-built loud speaker and tactile sound transducers system, a Bela Cape and Beagle Bone Black, near field photoelectric sensors and a synthesis and effects patch built in Pure Data (PD), a prototype of a hybrid acoustic - electronic instrument has been made. This prototype has been evaluated by five expert drummers and two co-performers in both group and solo settings in order to determine its effectiveness and potential role in professional music making.

Keywords Augmented drums · Electronic percussion · Music technology · Digital musical instruments · New interfaces for musical expression · Sound & music computing · Active acoustics · Hybrid instruments · Musical instrument evaluation

1 Introduction

Many musicians embrace the products of newly developed technology because of the new dimensions for personal expression they provide. As science progresses, the use of technologies such as electric pick-ups, amplification and mobile computing have led to creative possibilities for performers and new experiences for audiences, whilst disassociating cause and effect in a musical world where excitation can be remote from sound production [5, 9, 12].

Electronic percussion is a commercially successful field of musical instrument design. Beginners and professional musicians alike often have a digital drum kit, but they are not universally seen as a substitute for an acoustic instrument. They are also not seen at live music events as commonly as keyboards or even digital guitar effects pedals, this despite the advantages of portability and variety of sound characteristics that they exhibit. Research was carried out as to why this might be the case by reviewing drumming forums and magazines, in addition to five unstructured interviews with professional session drummers with regard to their use of electronic percussion. The resulting summary of pros and cons can be seen in Table 1.

The contribution described in this research is a digitally active drum that provides sonic capabilities associated with digital musical instruments—sounds that cannot be obtained from traditional acoustic instruments—in the form of an acoustic snare drum allowing full use of acoustic drumming gesture vocabulary, such as the use of brushes or muting with the palm of one hand. No attempt was made to provide either a highly portable instrument or to limit the instruments acoustic volume. Another contribution is the extension of evaluation methods, including those used in prior work[25, 26]. We use expert evaluation from musicians who primarily use acoustic instruments.

In Section 2.1, categorisations of electronic percussion and related work are presented. Section 2.2 introduces some of the many approaches that have been used for the evaluation of musical instruments. In Section 3.1, our design requirements along with the reasoning behind them are introduced. Section 3.2 describes the hardware Section 3.2.1 and software Section 3.2.2 used in DAD. Evaluation is presented in Section 4, including experimental set up and the various tests Section 4.1–4.6 that were carried out. Discussion is

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Table 1 Pros and cons of electronic percussion

Pros	Contras
• Low acoustic footprint	• Velocity sensitivity issues
• Easily transportable	• Aesthetic preference for acoustic sound
• Versatility	• Aesthetic preference for acoustic appearance
– Trigger any sound	• Dictates sound for recording (cannot use a microphone)
– Midi communication	• Not as responsive to playing nuances
– Audio-plugins support	• Feels very different to acoustic kit
– Samples of other drum kits	• Requires amplification, even for practice
– More exotic sounds	– Results in loss of collocation of sound
– Sound effects	– In the case of triggers, concerns associated with mixing of electronic to acoustic signals
– Built in signal processing	• Risk of technology failure
– Wavetable synthesis/physical modelling	• High repair costs
• Compact	
• No need for microphones	

split into four sub-sections: Evaluation method Section 5.1, Implications for models and frameworks Section 5.2, Design implications and future work and a summary Section 5.4. In Section 6, we summarise our findings.

2 Background

2.1 Related work

The first commercially available form of EP, the Moog Drum Controller Model 1130, was introduced in 1973. It utilised a piezo sensor in a plastic-skinned drum and a separately housed synthesiser [1]. Since then, the field of EP has expanded and can be sorted into the following over-lapping categories, which is condensed from previous work:[1]

- Electronic drum-kits take the form of a set of trigger pads arranged as an acoustic kit, which act as triggers connected to a separate sound synthesis unit. They are typically sold as a set and have a central unit that produces audio and facilitates parameter selection.
- Electronic Hand Drums are designed to be played with the hands, usually self-contained with the exception of amplification. Two products stand out in this category in that they allow different strike positions to change sound output. Handsonic is comprised of a several small pad zones. Piezo sensors are positioned at the edge of the pad and force sensing resistors (FSR) are placed under the sensor pads [22]. The Korg Wavedrum uses the acoustic sound of the drum head, detected through piezo pick-ups, to directly drive the synthesis—it could therefore also be considered a hybrid instrument [23]. This allows the experienced percussionist a great deal of nuanced control. This instrument is highly regarded but its first generation was not a commercial success. It has been suggested that its capabilities were not understood by its target audience, and that this contributed to poor sales [1].
- Individual Trigger Pads where the focus is on triggering high-quality sound samples. Triggers can be attached directly to acoustic drums and used to trigger an output in response to the acoustic input.
- Hybrid Systems preserve the acoustic qualities of the instrument in terms of interaction, sound output or both.

The following examples of electronic percussion are of particular relevance to this work.

- Roland V-drums use mesh heads, to reduce direct acoustic output and in-built conical triggers. Signal analysis determines radial strike position. Wavetable synthesis is output to an external amplifier.
- DDrum Hybrid Drums Series are a high-quality range of acoustic wooden shell drums with internally mounted triggers. The concept is very similar to Moog's Model 1130 but updated so that the audio output and the drum are both of much higher quality.
- Zildjian Gen16 are genuine acoustic cymbals but have been crafted out of a perforated mesh to reduce their acoustic output. They are equipped with a pick-up system mounted under the cymbal, and a signal processing unit that filters the audio to change the tonal characteristics of the sound output. With such hybrid systems, many of the nuances of acoustic technique can be used, but there is de-localisation of sound output.
- EL Cajon functions as a completely acoustic cajon, including internal snare wires.[2] It also has two internal sensors that trigger a wide range of user selected,

[1] https://tinyurl.com/sdgyumw

[2] https://www.roland.com/global/products/el_cajon_ec-10/

pre-loaded samples. The samples are played back through a front mounted speaker. This is a very simple, yet apparently very effective method of creating a hybrid instrument. This limits the user selection to samples rather than adding a variety of synthesis or sound effects making for a less complicated instrument.

- Aimi created Hybrid Percussion—a set of semi-acoustic physical controllers whose acoustic output was convolved with sampled instruments to produce expressive outcomes [1]. This consisted of a cymbal with a force sensing resistor (FSR) attached, brushes with attached piezo and flex sensors and a bass drum with piezo film sensors and feedback provided by a speaker. This research included evaluation by professional musicians via predetermined questions and informal interviews. Experts were allowed to freely explore the instruments. It is apparent from Aimi's observations that different musicians have differing approaches and requirements. He noted that experts could perform with latencies of up to 40 ms and were conscious of latencies over 15 ms. Whilst the work in this paper is most closely comparable with Aimi's, by contrast, we present a low latency self-contained instrument using an embedded development platform.
- With Emdrum, an electromagnetically actuated bass drum is used as a physical convolution layer applied to a signal collected by a microphone [18]. The performer can either tap or strike the microphone to create percussive effects, or sing or play an instrument into it. A moving magnet actuator induces vibrations into the skin of the drum, and a similar mechanism acts as a pick-up for the drum head. Feedback is then manipulated to change the response of the entire system. Whilst there is no apparent computing in EMdrum, Rector and Topel make the point that this electromagnetic induction pick-up/actuation system reduces any alteration to the physical properties of the drum skins, other than through the intended actuation. They point out that placement of the moving parts on the membranes of the drums is critical and that damping of the skin should be minimised.
- With the Bistable Resonator Cymbal, Piepenbrink and Wright experiment with a feedback loop combined with Digital Signal Processing (DSP) to alter the behaviour of an actuated acoustic cymbal [16]. The cymbal is clamped firmly on a rod and suspended from above. The lower end of the rod is attached to an audio exciter. Audio sensing is carried out either via hand-held microphone, which provides the best expressive possibilities, or via a piezo sensor sandwiched between the actuator and the cymbal. They describe a processing chain consisting of pre-amplification, equalisation, gating and compression.
- Maki-Patola, Hämäläinen and Kanerva built an Augmented Djembe Drum by mounting a webcam with a 70° viewing angle inside a djembe drum to capture the position and intensity of the shadows cast by the players hands [10]. These images are processed to control the loudness, tempo and timbre of a predetermined computer controlled rhythm pattern. This pattern is made up of layered samples of the djembe used as the controller. In this way, the performer has some level of expressive control over a computer controlled musical pattern. They can also play the djembe acoustically at the same time. This instrument was evaluated by six players with varying musical backgrounds. They were given set tasks and asked to comment freely, as well as answering set questions. The findings showed that the use of a real drum was pleasing to the musicians, and they reported that interaction felt natural. Opinions contrasted over the usefulness of a predetermined rhythm in terms of musical expression; one found it frustrating, another found it the most entertaining aspect. Latency was mentioned as an issue for some of the evaluation participants. PD was used as a prototyping tool, but a custom application was made for the evaluated version.
- In a review of Virtual Reality Musical Instruments (VRMI) and accompanying design proposals, Serafin et al. use the term 'magical' to describe instruments or interactions that are not bound by the laws of physics [20]. They also suggest that Natural and Magical interactions should be considered when designing a VRMI. In this paper, the term magical will be used to describe sounds that could not normally come from an acoustic drum.

2.2 Evaluation methods

There are many frameworks for design and analysis of musical interfaces. They range from propositions for dimension space representations [6] to simple lists of design principles [8]. The instrument evaluation method used in this research was built upon and extends a number approaches including the following key works.

Barbosa, Malloch and Wandereley [3] carried out a review of evaluation methods used in the New Interfaces for Musical Expression (NIME) community over the period 2012–2014. Their findings revealed a number of different understandings of what evaluation might mean and widely varying, sometimes poorly defined goals and targets. They acknowledge evaluation goals, targets and stakeholders vary depending on the nature of project in hand, but argue for more clarity. The question raised by the paper is not 'should we evaluate?' but 'how?' and 'how should the results be used?'.

O'Modhrain presents us with a framework for evaluation [14] which accounts for the multiple perspectives that can be adopted in Digital Musical Instruments (DMI) appraisal. She identifies three key stakeholder perspectives: The *Audience*, the *Performer* and the *Designer*. It is often and convincingly argued that the performer's evaluation is the most critical when considering a new musical instrument [1, 14, 26].

One perspective that has not been addressed by any of the literature that the authors have reviewed is that of the co-performer. This perspective is likely to share attributes with the performer and audience perspectives, but may have their own unique insights, we therefore extend prior frameworks to include the co-performer in the evaluation of DAD.

Data derived from evaluation can be either qualitative or quantitative. With regard to quantitative data, various Human Computer Interaction (HCI) tests have been adapted for use with DMI. In a previous project [26], an adapted System Usability Scale (SUS) test was used to evaluate a digital shaker. This approach has been used to evaluate other musical instruments, but data cannot easily be compared as both SUS adaptions and musical instruments differ. We therefore use the same test on DAD to give more meaning to the data obtained in both projects.

3 Designing DAD

3.1 Initial interviews and design requirements

The research presented in this paper focuses on a snare drum because it plays a central role in the contemporary acoustic drum kit. The snare mechanism, which gives the snare drum its name and characteristic sound, is made up of a set of wires that are held over the lower, resonant head and tensioned by the snare tensioner. When the upper, batter head is struck, a shock wave sets the resonant head into motion resulting in the snare wires rattling against it. The tuning of the resonant head, the materials used and the number and tension of the snare wires all affect the sound of the drum.

Unlike Berdahl's Haptic Drum [4], the focus of DAD is to provide the sonic capabilities of digital processing whilst preserving the traditional interaction methods of an acoustic drum. There are numerous techniques that can be used to play the snare drum. Some are listed in [22], but that list is far from exhaustive. A series of preliminary, informal interviews were conducted with professional session drummers as well as amateur rock, pop and jazz drummers. This was done to determine what specific benefits an active snare drum might provide.

Some key suggestions included …*Division of the batter head into regions with different responses*, *Respect for the center of the drum as it is the main working area*, *Respect for the batter head in general, preferably no damping of its natural resonances*, *allowance for different techniques and nuanced control* and *co-location of sound and instrument*. In addition to these requirements, a variety of digital capa bilities had to be chosen to present the advantages of EP.

The resulting design goals were:

- Low latency.
- Collocation of sound. Collocation is considered as one of the advantages of acoustic instruments; indeed, it is one of their defining qualities. This is achieved by mounting a speaker directly in the drum and by actuating the drum with audio exciters.
- Digital augmentation should not obstruct choice of technique. Drumming techniques are numerous and vary from drummer to drummer. Mapping was predominantly designed to be continuous rather than discrete, tracking the vibration of the drum-skin rather than identifying technique directly.
- Striking the centre of the batter head should produce a snare like sound, whilst different areas of the drum can produce assignable sounds. This is done by providing two differently mapped areas of the drum head, one central and one off centre (acentric). These areas are adjustable in sensitivity and surface area (Table 4).
- Variety of digital audio signals. In order to present the possibilities of electronic percussion, a variety of sounds and approaches have been provided—Synthesis of snare mechanism and drum skin through two different subtractive synthesis patches, delay-based sound effects and sample playback. Within these modules, responses from the *natural* to the *magical* are possible.

3.2 Implementation

3.2.1 Hardware

DAD was built by augmenting a standard snare drum to afford the musician the sonic capabilities of electronic percussion whilst preserving the interaction quality of an acoustic instrument. A block diagram of the hardware system is provided (Fig. 1). Bela Cape[3] and Beagle Bone Black were chosen for low latency and availability of audio-rate analogue inputs. An Arduino Mega[4] was used for less latency sensitive parameter control—two potentiometers, in conjunction with some push button switches, to change various parameters. Two QRE1113 Minature Reflective Object Sensors measured the vibration in the batter head, and they were mounted on thin wooden slats, which were elasticated in place with height-adjusting bolts positioned underneath them to allow adjustment of

[3] https://bela.io/

[4] https://www.arduino.cc/

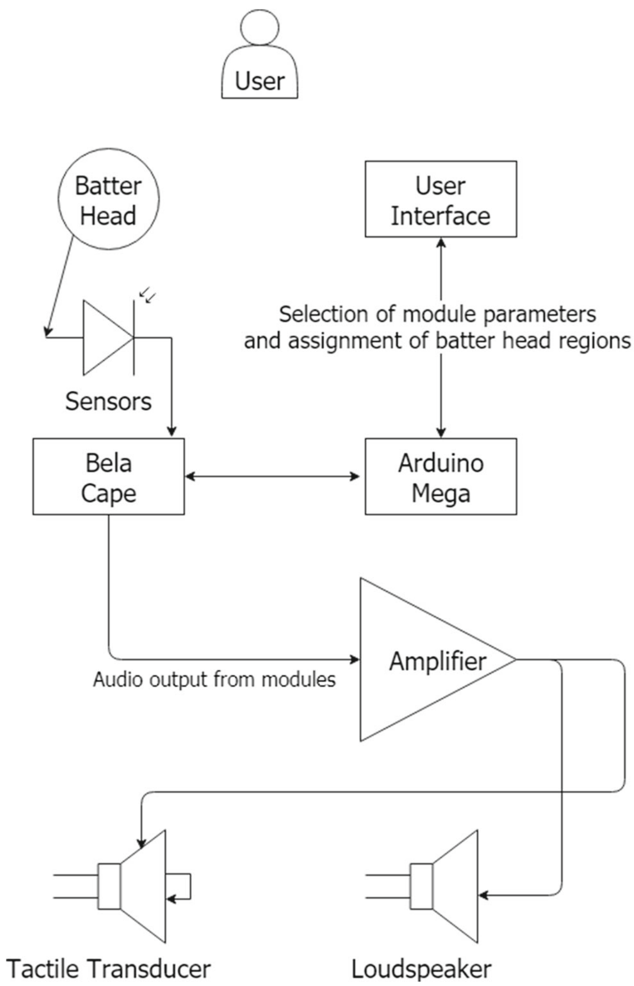

Fig. 1 Schematic of the DAD hardware system

their vertical position. These sensors were chosen because they have proven effective in other related research, and they have the advantage of not restricting the movement of the batter head [15, 21].

Two Dayton Audio tactile transducers with a nominal impedance of 4 Ω and a power handling of 20 W RMS were connected in series and attached to the drum's resonant skin with double sided adhesive tape. The tactile transducers and a 50-W mid range speaker were powered by a 20-W audio amplifier. A laser cut MDF frame was bolted to the inside of the drum shell using the existing tuning bolt housings and was braced at either edge with a rectangular cross-sectioned strip of wood. The loudspeaker is slotted into a hole cut into the wooden frame and is held in place by bolts threaded into nuts trapped in a circular bracket (Fig. 2).

The development boards, push buttons and potentiometers were housed in a laser-cut and engraved housing, which was bound to the outside of the drum with elastic strips. An array of light emitting diodes (LED) was added to this unit, which acted as a *User Interface* (UI) Fig. 3.

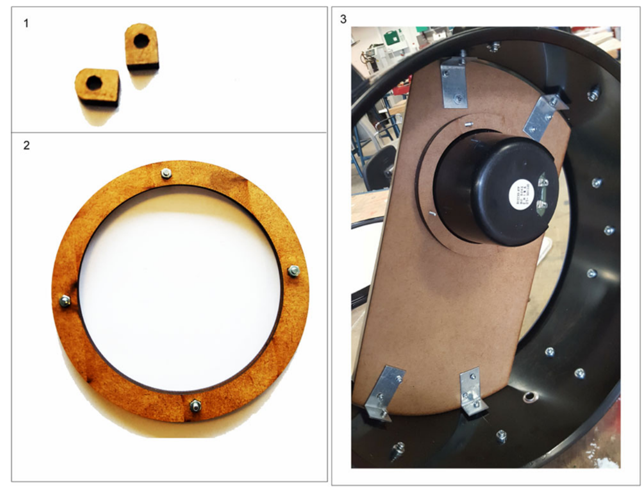

Fig. 2 Speaker Bracket System 1. Nut retainers 2. Laser Cut Bracket 3. Speaker Frame in Position Inside DAD

3.2.2 Software

Four software modules were designed for DAD. They are summarised in Table 2. Synthesis, effects and sample playback are carried out in Pure Data (PD).[5] In keeping with the practice observed in commercially available EP, an emulation of snare mechanism and drum acoustics is provided. It is not intended that a *life–like* sound should be produced (the original acoustic snare mechanism could be reattached for that purpose), but rather an indication of how realistic sounds could be used and adjusted, and within the same set of controls more *magical* sounds can be dialled in, such as extremely long snare mechanism delay times. Signals from the optical sensors were preprocessed via a high pass filter[6] (to remove DC, reduce mains hum and to moderate artefacts found to occur due to sub-audio signals produced when striking the drum with bare hands), then raised to a user adjustable power to adjust proximity sensitivity.

The snare mechanism software module is based upon using Cook's *Physically Informed Stochastic Event Modelling* (PHISEM) algorithm [7]. The root mean square (RMS) amplitude of the preprocessed centre sensor signal modulates the output of the PHISEM patch. A white noise signal is used to generate random impulse signals. The resulting signal has an amplitude envelope applied to it, which is adjustable via the UI (Table 3), this models a series of collisions of small particles. This is further processed by a user filter, controlled via the UI, to give the impression of different materials being involved. A 1-ms attack time is applied to it to maintain a smooth output. The release time

[5]https://www.arduino.cc/

[6]Cut off frequency 150 Hz for snare mechanism, and 100 Hz for subtractive synthesis and sample playback modules

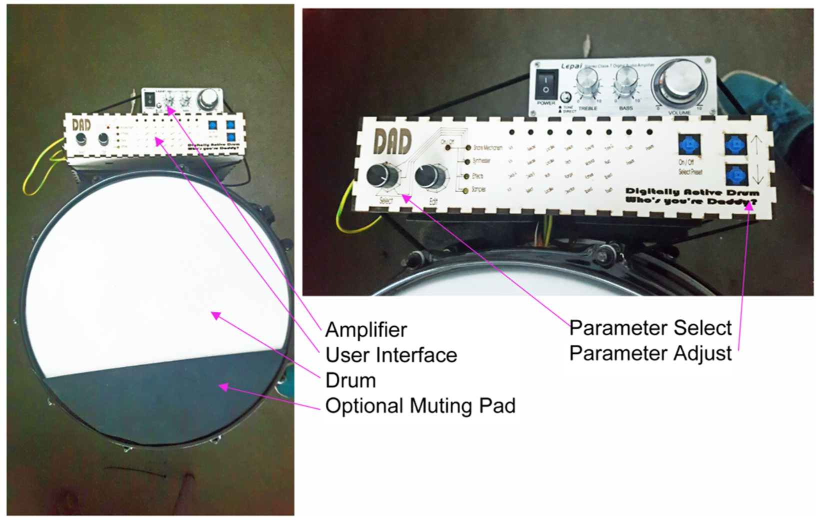

Fig. 3 Players view of DAD

is adjusted via the UI allowing for interesting, potentially *magical* effects. The signal is then amplitude modulated by a sawtooth wave. The frequency and gain of the sawtooth modulation can be adjusted via the UI. This models the snare wires repeatedly hitting the resonant head at a rate dependent on their tension.

The subtractive synthesis software module provides a parametric model of a struck material. A user controlled gain acts as a sensitivity adjustment before the signal is sent to the PD object *bonk*~, which detects percussive onsets by looking for changes in spectral composition [17]. The amplitude of the reported onset is used to create an amplitude envelope for the synthesised sound. The surface of the drum is divided into two user adjustable regions, one centred in the middle of the drum (central region), and one located off centre (acentric region) (Fig. 4). The output of the subtractive synthesis and sample playback modules can be assigned to either of these regions via the UI. The subtractive synthesis model is built from one sawtooth wave that is filtered by three narrow band pass filters. The centre frequency of the lowest filter and the mathematical relationship between it and the other two filters can be changed via the UI. The width of these filters can be adjusted and their centre frequencies can also be modulated by a sine wave. When fed into the drum, it takes on the physical resonance of the instrument and blends into the acoustic sound.

The delay-based effects can be applied to the outputs of the snare mechanism and/or subtractive synthesis modules. Two delay lines are connected in series to create a ping pong delay, the output from each delay is sent to a different output (loudspeaker or tactile transducers). The length of these

Table 2 Summary of software modules designed for DAD

Module	Description
Snare mechanism	PHISEM-based subtractive synthesis. This can model a snare mechanism or other sounds based on multiple collisions.
Subtractive synthesis	Can produce drum-skin like sounds or resonances materials such as, for example, metal or glass.
Delay-based effects	Delay, echo, flanger
Sample playback	In principle any sample could be used, and played back in any direction or sample rate.

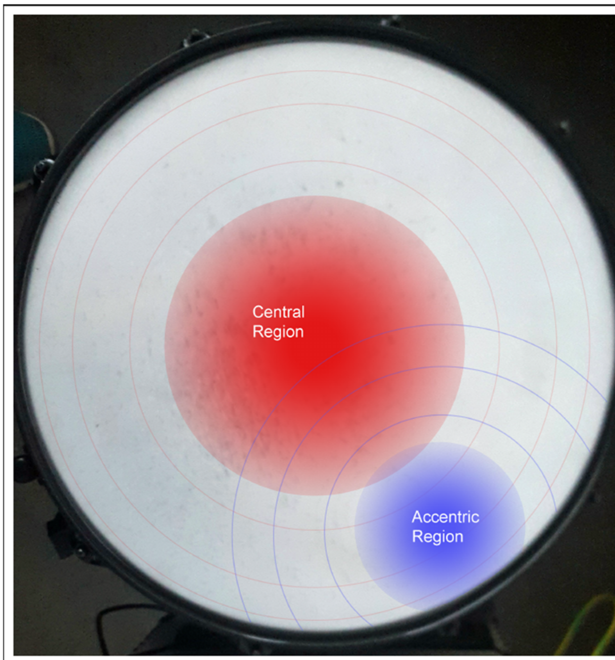

Fig. 4 Topographical mapping regions

Table 3 Drummers taking part in evaluation

Drummer	Age	Years playing	Self-assessed playing standard	Preferred genre	Took part in
Participant A	39	27	Semi professional	Jazz	Solo session
Participant B	46	7	Keen amateur	Funk, Samba	Solo session
Participant C	53	37	Professional	Jazz	Solo session
Participant D	35	24	Professional	Rock and Pop	Group session with guitarist /pianist and bassist
Participant E	50	40	Professional	Jazz	Group session with vibist and bassist

delay lines can be controlled via the UI. A user adjustable flanger effect was also implemented.

The sample playback module allows preloaded samples to be triggered by striking the drum in either sensor region at rates, playback directions and trigger sensitivities that can be adjusted via the UI. The overall amplitude is set by the detected onset amplitude. Four samples were provided; a cowbell, a china cymbal and a crash cymbal represented *natural* percussion sounds, and male hysterical laughter was chosen as a *magical* option.

To measure latency, a microphone was situated 50 cm from DAD at an angle of 45° to the plane of the batter head. The signals from the microphone and from the jack output of the Bela Cape were connected to separate inputs of an audio interface. DAD was then struck, centrally, with a drum stick twenty times in succession at intervals of approximately 1 s. The resulting stereo audio file was then loaded into Sonic Visualiser,[7] and the time intervals between onsets across channels measured individually. The mean average of the latencies was taken as the latency and Jitter as the maximum deviation from the mean. The latency using only the snare mechanism synthesis was 11.15 ± 1.2 ms, using only the subtractive synthesiser module gave a result of 15.96 ± 6.3 ms. This is marginally higher than the often quoted 10 ms threshold [24], but well within those observed by Aimi [1, 11].

4 Evaluation

Expert evaluation was carried out in five sessions, over 5 days with expert performers (drummers) and two co-performers, three including the first author (piano/guitar, vibraphone and bass). Five experts were considered an adequate sample size for usability tests, based on usability test research [13]. The music performed was within the genres of rock, pop and jazz. Each session was video recorded, extensive notes were taken during and after each evaluation session and questionnaires were filled out by all participants which were used to help develop detailed discussion during evaluation.

Each test was designed to evaluate specific aspects of DAD and to simultaneously elicit relevant feedback. Drummers ages, experience and details of which sessions they took part in can be seen in Table 3. All had played EP before. Co-performers included a guitarist/pianist, a vibraphonist and the first author, on bass ukulele and bass guitar. The only non-professional musician taking part described himself as a keen amateur and plays caixa rather than drum-kit.

Three solo sessions were carried out on the Aalborg University Copenhagen campus. These took 2 h to complete. A set of drumsticks, beaters and brushes were provided.

Two group sessions were held in different rehearsal rooms in Copenhagen, each took 3 h. These consisted of one drummer, one co-performer and the first author. The principal aims of these sessions were to test for the success criteria that DAD could function as a snare drum in a group situation and to explore the perspective of the co-performer. Video review was used to support evaluation.

Each drummer had been asked to bring their own drum and were asked to play it for a few minutes, first with its snare mechanism engaged, then disengaged. This was done to establish a reference drum sound and behaviour as a baseline.

4.1 Perception test

In order to determine how natural sounding DAD was with various pre-set subtractive synthesis sounds being triggered, how discoverable the topographical mappings (Fig. 4) were and if the injection of synthesised tones into the drum made the interaction less clear, each drummer was asked to play DAD in each of six states. One state without any effect, and five with different pre-sets chosen to present a variety of subtractive synthesis sounds. All sounds were at similar volume levels and were designed to sound natural.

[7] https://www.sonicvisualiser.org/

The topographical mapping and sensitivity settings were different for each pre-set. The pre-sets were presented in the same cyclical order, but each musician started on a different pre-set. Each drummer was given several minutes to experiment with each sound and asked to rate the drum setting, on a seven point Likert scale, for a number of criteria, listed along with respective justifications, in Table 4. Participant behaviour and comments were passively observed and noted. If the participant did not explore the whole batter head, they were then prompted to do so. The experiment was then discussed, further comments noted and the drummers were encouraged to explore the pre-sets again.

Three of the five drummers were unable to immediately determine a difference between pre-sets, two of these did not detect the synthesis module until the off state pre-set was presented. One drummer did not make any statement suggesting that he had heard a change in the sound of the drum, but remarked that it seemed easier to play when the off-state pre-set was selected. Neither co-performer commented on the differences in pre-sets without prompting. In further discussion, it was revealed that they had both heard the decay of the subtractive synthesis model but had attributed it to resonances in the room.

It was apparent that the topographic region markings on the batter head (Fig. 4) were not very clear, as only one drummer saw them, and this was because he had placed a lamp above DAD to help with video recording. The three most experienced drummers discovered the topographical mappings (Fig. 4) without prompting. With only five drummers having taken the test, there is little point in extensive statistical analysis, but a clear trend, in the Likert tests favouring the acoustic instruments without synthesis was visible for clarity and general preference (Fig. 5).

4.2 Initial evaluation

The UI was introduced, and section by section, the control and concepts of each module were explained (Table 2). At each stage, the participant was encouraged to explore the possibilities that the section afforded them, and to generally play the drum, with whatever technique they wished. After having played with all the available settings for one module, the participant was asked to consider the five keywords: *Mentally, Physically, Timing, Frustration and Engagement*, and rate how easy or difficult, or good or bad the experience was. A 5-point Likert scale was used. They were also encouraged to comment freely on the experience. These test parameters are derived from the NASA TLX tests. This has been used to test playability of an instrument in other studies [27].

All five drummers stated that the snare mechanism synthesis could not be a substitute for their own instrument, but that the topographical mapping reacted quickly enough and considered that the sawtooth amplitude modulation gave an impression of a loose set of snare wires. Participant C: '... it's not accurate enough, it sounds like a shaker... ' ... Participant D: '... if it was my usual snare I would fix the snare by tuning up the resonant skin...'

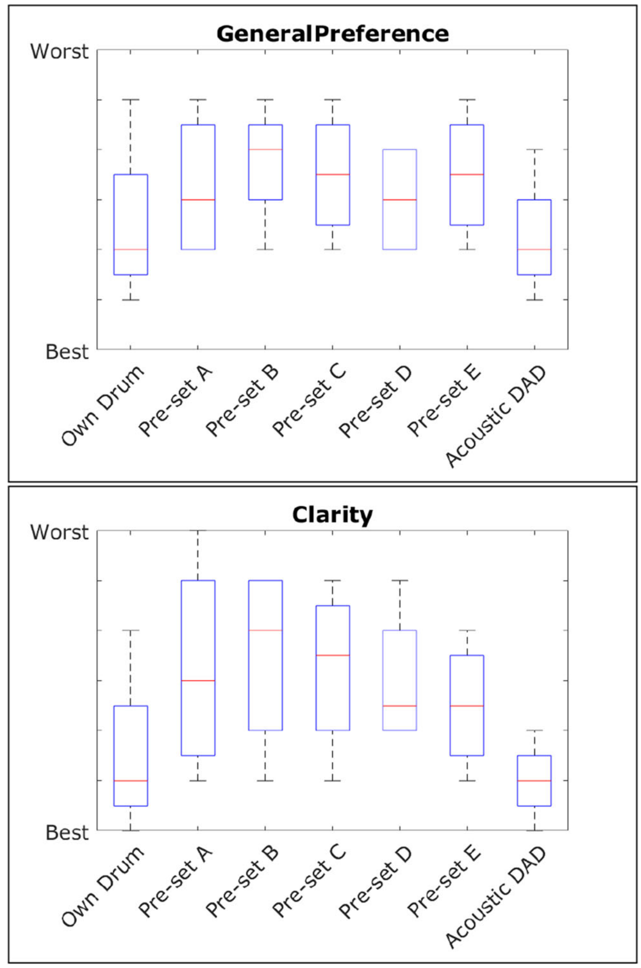

Fig. 5 Likert results for general preference and clarity

Table 4 Choice and justification of Likert criteria

From a study into how musicians evaluate violins [19]	Resonance, richness, clarity, balance and playability
An indication of how *realistic* the effect of injecting the synthesised sound into the drum was	Naturalness
To determine if the instrument will hold the musician's interest	Engagement
To test the reliability of the mapping	Dynamic control
To give an overall impression of whether the drummer preferred the acoustic drum	General preference

Opinion was split about the value of the snare mechanism synthesis. Three drummers and one co-performer stated that they liked it a lot, one drummer did not like it and doubted he could ever use it, the remaining participants had no strong feelings one way or the other. Some drummers felt that the more extreme, *magical* sounds were '...great fun...', experimentation often led to spontaneous solos. All but one drummer suggested that the sound of their own snare sound was very personal, and that they would likely be unhappy unless they could match it very closely. Participant B: 'I have a very specific idea about how I want my snare to sound and I don't have a great deal of interest in varying it'.

Both co-performers stated that the snare mechanism sounded realistic in group performance. One co-performer observed that one of the pre-sets sounded almost exactly like an acoustic snare with a small splash cymbal on the surface of the drum—there was artistic value in a stochastic synthesis that does not sound exactly like a snare mechanism. However, the scores for the snare mechanism show that it tended to be less playable than all the other modules (Fig. 6.).

In contrast to the response to the snare mechanism module, which was verbally criticised by all but one drummer, the sounds produced by the synthesis module were greeted with enthusiasm. All commented that they were inspired to change their playing styles, and this could also been seen and heard in video recall. All, including the co-performers, noted that the sound somewhat dictated how they played.

The introduction of the acentric topographical mappings resulted in all the drummers commenting that they changed their perspective in evaluating DAD. They shifted paradigm such that they no longer considered it a snare drum. For example, the ability to affect markedly different sounds by striking specific areas of the drum, i.e. acentric and central regions (Table 4) made good sense to one expert, his experience of cajon playing was then utilised to explore different sounds in different places on the drum. DAD made more sense to him from this point on. No two drummers cited the same instrument, but a cajon, a steel drum and a hang drum were all mentioned. One stated that he felt it was more suited to percussionists such as Trilok Gurtu or Airto Moreira, who have a set-up comprised of parts of a drum kit and several items of percussion.

The playability ratings show that most drummers found DAD more difficult to play whilst the snare synthesis module was active than with any of the other software modules. This fits with their comments regarding preference for an exact snare sound, but it could also indicate a learning curve as they had begun to understand more of the concept behind DAD (Fig. 6).

It was only the most experienced drummers who appeared to have the ability to accept DAD's more *magical* responses, such as delay. Participant E immediately responded 'It's crazy, I love it', and immediately played an extended solo based on that effect alone.

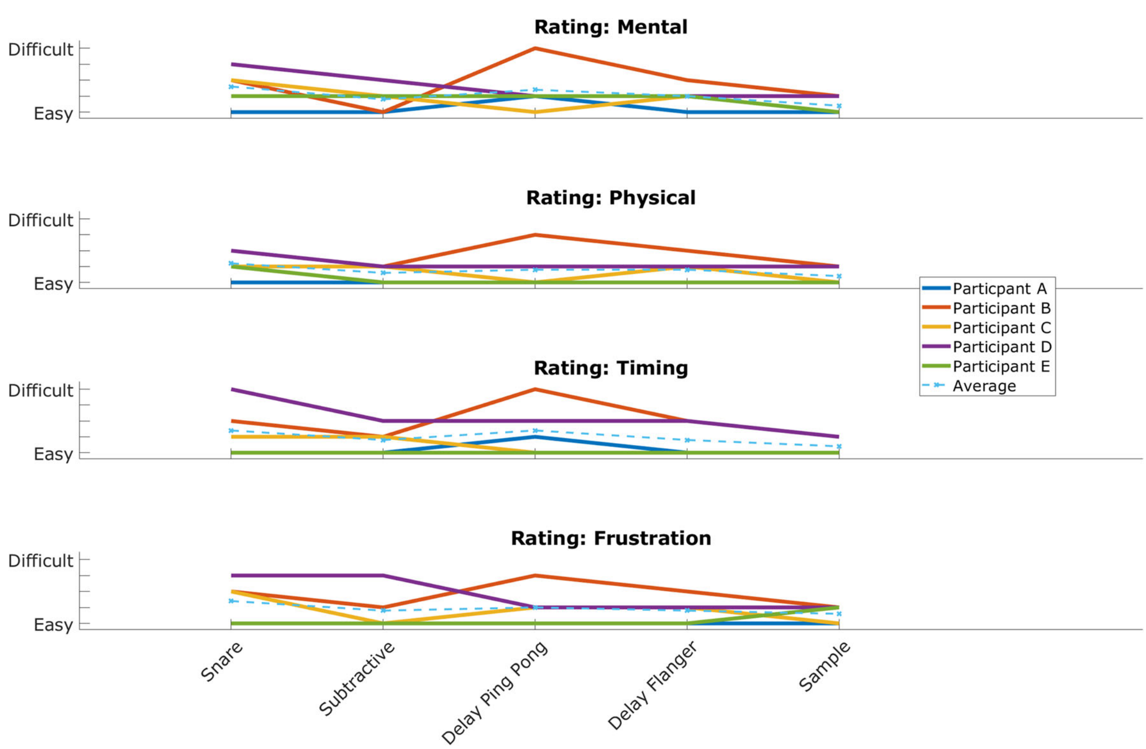

Fig. 6 Playbility scores for all drummers

4.3 Solo video recording

Drummers in the solo sessions were asked to adjust the settings of DAD according to their taste and invited to perform a short solo, which was video recorded. This gave an indication of each performers preferences in terms of DAD's capabilities as well as encouraging them to explore DAD creatively for open evaluation purposes and providing video review material for observation.

4.4 Comparison test

The participant was asked to compare DAD with their own snare and state which of the two they felt was best according to the criteria: *Experienced freedom and possibilities*, *Perceived control and comfort*, *Perceived stability, sound quality and aesthetics*, *Learnability*, *Explorability*, *Feature controllability* and *Overall experience*.

All but one drummer stated that DAD outperformed their own snare with regard to *Freedom and possibilities*, another felt restricted by DAD's response in this respect. His comments suggest that he was trying to reconcile his internal model of a snare drum with DAD's response. This restricted his sense of freedom on the new instrument. All drummers indicated that DAD was more explorable than their own drum. In every other respect, DAD came second to a traditional instrument.

4.5 System Usability Scale

An adapted form of the SUS test was taken by the drummer participants in order to determine if the concepts of control and interaction were understood and practically implemented. This test was the same variant of SUS that had been developed for Extended Actuated Digital Shaker (bEADS) [26].

SUS scores were low for DAD compared with bEADS, where the same test had been used [26]. Whilst SUS was developed to asses the usability of systems such as websites or telephones, it has been used in musical instrument evaluations. To do this, the standard questions have to be reworded, and the scores interpreted differently. DAD scored an average of 43 with a standard deviation of 3.26 in this study. This would equate to somewhere between *bad* and *poor*, according to a study by Bangor et al [2]. Frustration with the perception tests and dissatisfaction with the quality of the snare drum may have left a negative impression on the participants, but low SUS scores are not necessarily indicative of a poorly designed instrument. All the drummers and one of the co-performers suggested that DAD did not function as a snare drum. This low score is attributed to, on the basis of comments made during open discussion (see below), the required adjustment to a new internal performer model of the instrument and the confusing UI.

4.6 Basic tasks and open discussion

The following questions were asked of the drummers: *Can you play at a steady tempo?*, *Can you incorporate a localized sound into a pattern?*, *Can you play freely (sound effects)*, *Is it possible to quickly change timbre?*, *Are you able to make musical use of variation in sound?*, and *Are you able to play dynamically?*, *Are you able to use a variety of techniques and still make use of DAD's features?*

Time was then allowed for a general discussion about the session.

DAD performed well in this test; however, the musicians with the most professional experience were more critical. This could indicate that they are more sensitive to the limitations of an instrument due to their higher level of skill and control.

One drummer believed it would be possible to perform only using an instrument like DAD, at smaller concerts, giving him the capability of playing an acoustic instrument and triggering samples of other kit drum instruments from that single instrument. Although this was not within the design goals of the prototype, it does address the aspect of portability raised in Table 1.

5 Discussion

5.1 Evaluation method

This research used expert musicians in evaluation of a musical instrument, and other studies have used the same approach [1, 14]. A talented professional percussionist will be able pick up almost any object and make music with it. One has to be wary then, as the observer, to judge the instrument and not the performance. However, such talented musicians are in the best position to search out the expressive limits of a new instrumental design, especially one based on an existing traditional paradigm. In order to guard against the possibility of studying musicianship rather than testing DAD's potential as an instrument, a range of drummers with different abilities were sourced, including a dedicated novice musician who was in a position to test entry level expressive possibilities in a way that neither a complete beginner nor arguably a professional musician could.

5.2 Implications for models and frameworks

O'Modhrain identifies the audience, the performer and the designer as the main stakeholders in DMI evaluation [14].

In this paper, a fourth potential stakeholder, that of the co-performer, has been proposed.

It was assumed that the co-performer's perspective would be somewhere in between the audience and performers. More informed than the audience, but from an observers point of view. This proved not to be the case with the two co-performers used in this study. They were unconcerned with the mechanics behind the interaction with DAD (at least whilst performing) and were focused on the sound and musical role of the instrument. The performer, designer and the audience are concerned by the physicality of interaction with a musical instrument in different ways—feel and ease of use in the case of performer, visual impact for the audience, both for the designer. It appears from this study that a co-performer may not be impacted by the visual aspect of the interaction, only being concerned with the sound being produced. Their viewpoint, the authors argue, is critical to the uptake rate of new instruments, as being integrated into group playing situations is likely to be a critical element in the instruments acceptance.

Context was also very important for the performer. Absorbing DAD into a drum kit apparently changes the role of the instrument, restricting the extent to which the drummer can explore it. When using DAD as a stand alone instrument, or when playing solos participants wanted more outrageous sounds, they were not interested in subtlety. This observation was made by Aimi with regard to at least one of the experts he worked with [1]. However, in group situations, these ear catching sounds needed and demanded space, so a more discreet set of sounds was required.

5.3 Design implications and future development

The goal of the snare mechanism synthesis was to provide an adjustable pseudo-snare audio output. It was intended to represent possibilities rather than recreate a snare mechanism. This approach did not account for the requirements of the musicians taking part in the evaluation. The specific sound of a snare mechanism was apparently a necessary component in their internal performer model [14] to such an extent that they could not happily interact with DAD as a replacement snare drum. Any future version of DAD should take steps to address this by refining synthesis, using a full range speaker and/or retaining the physical snare mechanism.

Realistic synthesis of drums is a significant technical challenge, and one that is beyond the goals of this study. A simple and direct solution would be to remove the tactile transducers from the resonant head and reinstall the snare mechanism, any snare mechanism synthesis would then augment the acoustic signal.

The SUS score for DAD of 43 was low; however, SUS tests were developed for determining the effectiveness of interaction design for less abstract systems than musical instruments. It is more suited to appraising web designs or computer operating systems. It has been adapted for use for new musical instruments but lacks a systematic method of interpreting results. It could be that the score of 43 for DAD is indicative of an instrument that requires more time to master. It cannot be denied that the user interface and the need for intuitive control of parameters need to be refined. It should also be noted that this low SUS score fits with analysis of Wavedrum's poor commercial performance in that some reviewers believe it was too complicated.

5.4 Evaluation summary

In group settings, DAD functioned as a snare drum only from the point of view of the co-performer. The level of synthesis precision that drummers in this evaluation required before being able to happily use DAD as a snare drum was underestimated. Co-performers could hear the difference, but felt that DAD functioned as a snare drum.

DAD definitely provided expressive possibilities beyond that of an acoustic snare drum. All the evaluating drummers found the expressive range available to them entertaining and captivating. This applied to the new sounds coming from the drum *and* the way that existing techniques such as muting and using brushes could give novel results.

All the drummers who took part in the evaluation were interested in the prototype. It should be noted that whilst DAD does appeal to the target demographic, their view of the instrument was almost universally that it should be considered a second snare drum. In such a role, four out of the five drummers said they would definitely consider using it.

An evaluation methodology has been outlined, with appropriate resources, this could be extended to include coding of qualitative data through methods such as video cue recall, larger sample sizes and a number of different musical instruments.

6 Conclusion

After testing with five drummers and two co-performers in solo and group performance session, suggestions for improvement and verification of design concepts were obtained. The current implementation points to an instrument that is more suited to use as a second snare drum, or as a snare-drum-inspired new musical instrument for solo use (not as part of a drum kit). In order for it to be considered as a replacement snare drum, the snare mechanism synthesis would have to be significantly improved, or a genuine physical snare mechanism should be installed.

SUS results indicate that the UI should be simplified. The amount of variables should also be kept to a minimum.

DAD allows the exploration of a new sonic landscape. The skills and gestures built up over years of study can take on new meaning, or be returned to their original context at the flick of a switch. However, the current prototype needs significant improvement both in terms of synthesis and in the integration of controls, followed by further extensive expert evaluation before this can be fully realised.

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Data availability All supporting data is available on-line. http://www.peterwilliams.dk/dad-digitally-active-drum/

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